Response of canola to different seed-row placed fertilizer phosphorus forms, opener configurations and rates of application

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by

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ABSTRACT

Maintaining canola yields requires that phosphorus (P) removed from soil in crop harvest is replaced through P fertilizer application. Rate of P fertilizer application, form used, and method of placement are important factors that influence the crop utilization and yield response to added P. The objective of this thesis work was to assess the influence of P fertilizer application rate, form (mono ammonium phosphate versus struvite) and seed-row opener configuration (narrow versus wide opener spread and row spacing) on canola (*B. napus* hybrid var LL 252 & L 233P) under controlled environment and field conditions. In the controlled environment study, application of P fertilizer (MAP) at 20 kg P_2O_5 ha^{-1} significantly increased early (30 days after seeding) above ground biomass yield compared to the unfertilized control, while further rate increases produced no statistically significant yield increases. Struvite (ammonium magnesium phosphate) performed similar to the mono ammonium phosphate in crop yield response, fertilizer P uptake and recovery. The narrow seed-row opener spread (1”) gave better canola yield response and recovery of P from the two seed-row placed P fertilizers compared to the wide (3”) spread, which is attributed to greater localized concentration of P fertilizer in the narrow spread with concomitant reduced fixation in the soil. Canola emergence after 5 days was delayed with the high seed-row placed P fertilization rate of 60 kg P_2O_5 ha^{-1}, but the differences among rates were not significant and the emergence recovered at day 10. In the field study, conducted in 2019 at five sites across SK and AB (Saskatoon, Brooks, Lethbridge, Melfort, and Scott) using mono ammonium phosphate as the P source, canola had significant positive biomass yield (above ground plant material at maturity) responses to P fertilization at most sites, with the greatest incremental yield increase associated with the addition of 22 kg P_2O_5/ha, with responses levelling off at higher rates. Across the sites, the canola biomass yield and P uptake was maximized at rates of 39 to 56 kg P_2O_5 ha^{-1}. At Brooks, Scott and Lethbridge, significantly higher canola biomass yield and P uptake were observed using the highest seed bed utilization (44%) configuration, which was the combination of widest opener spread (4”) with narrowest (9”) row spacing. Limited and non-significant effects of seed bed utilization were observed at Saskatoon and Melfort sites. The benefit observed from having higher seed bed utilization at three of the five sites in the field study may be explained by greater early season root exploration of the soil volume associated with greater dispersion of seeds and fertilizer

throughout the seed bed, with negative effects of greater opener spread that were observed in the controlled environment study not apparent under field conditions.

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DEDICATION

I gratefully dedicate this work to my parents, Zhiqiang and Jing, who have continuously supported me in studying aboard and obtaining higher education.

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LIST OF ABBREVIATIONS

Aluminum	Al
Ammonia	NH_3
Analysis of Variance	ANOVA
Calcium	Ca
Carbon	C
Cation Exchange Capacity	CEC
Chloride	Cl
Completely Randomized Design	CDR
Diammonium phosphate	DAP
Distilled	DI
Electrical Conductivity	EC
Fluorine	F
Fourier transformed infrared spectroscopy	ATR-FTIR
Magnesium	Mg
Modified Kelowna	KM
Mono ammonium phosphate	MAP
Nitrogen	N
Orthophosphate	$H_2PO_4^-$
Phosphoric Acid	H_3PO_4
Phosphorus	P
Phosphorus use efficiency	PUE
Plant Root Simulator®	PRS™
Randomized Complete Block Design	RCBD
Secondary orthophosphate	HPO_4^{2-}
Seed Bed Utilization	SBU
STRUVITE	$MgNH_4PO_4{\sim}6H_2O$
Sulfur	S
Thousand Kernel Weight	TKW
X-ray Absorption Near Edge Structure	XANES

1. Introduction

1.1 Phosphorus Fertilization Practices in Western Canada

To meet the increasing demand for canola yield, prairie producers apply rates of phosphorus (P) fertilizer to supply sufficient P for the current crop, as well as attempt to replace the phosphate removed from the system by crop harvest and losses such as erosion of particulate P and transport of soluble P in water (Wiens et al., 2019). There are numerous phosphorus fertilizer forms available on the market, including monoammonium phosphate (11-52-0), diammonium phosphate (18-46-0), triple superphosphate (0-46-0), liquid ammonium polyphosphate (10-34-0), magnesium ammonium phosphate (struvite), as well as "organic" P in amendments such as manure, compost, and sludge that can be used to meet crop requirements for P. Some research has reported ammonium polyphosphate, which is a liquid P fertilizer, to perform better in comparison to granular P fertilizer in alkaline, calcareous soils (Bertrand et al., 2006; McBeath et al., 2007). However, liquid P fertilizer is more expensive than granule P fertilizer, and its benefits have never been clearly shown in western Canada (Grant et al., 2001). Among the granular P fertilizer forms, monoammonium phosphate (MAP) with numeric designation 11-52-0, dominates as the P fertilizer form used by growers in western Canada today. Monoammonium phosphate is widely used by canola growers in Western Canada, representing about 65% of the P fertilizer used, with the other 30% typically applied as ammonium phosphate sulfate product (Fertilizer Canada, 2020). The MAP product contains the highest P content among P fertilizer products. The common method of manufacturing MAP is to react ammonia (NH_3) with phosphoric acid (H_3PO_4) at one-to-one ratio and then solidified in a granulator to produce a granule that when applied to soil, will readily dissolve in the soil solution.

Struvite based P fertilizer is a new granular P fertilizer product that has recently become available for growers in Western Canada to use. The struvite ($MgNH_4PO_4{\sim}6H_2O$) or magnesium ammonium phosphate is a P-containing mineral that exists in nature which can also be manufactured through precipitation from municipal wastewater streams and from liquid manures such as hog manure. Commercial struvite fertilizer produced from municipal wastewater in Western Canada has the numeric designation 5-28-0 with 10% Mg by weight. Struvite is promoted as a better choice for sustainable agriculture due to its origin as a recycled product, but availability to the plant in early stages may be lower, as it is reported to dissolve best under low pH conditions including rhizosphere via protons released by root or organic acids (Grant & Flaten, 2019). Seed-row placed P fertilizer has its greatest benefit from its ability to provide early P availability to seedlings and promote early-stage crop growth; but the application rate is limited by the salt tolerance of the seed. Using struvite as the P source might be effective in reducing early-stage salt damage to seedlings but may also have reduced plant P uptake and recovery potential due to low solubility. However, there is little information available on the effectiveness of struvite as a P source for crops in Western Canada in comparison to traditional monoammonium phosphate fertilizer.

Annual crops should be supplied with sufficient phosphorus at very early stages as P is needed for energy production, cell division, and growth including initial processes in seed germination and seedling emergence, and in plant metabolism all the way to plant maturity. Although P is required continuously during plant growth, the P supply in the early growth stages is known to have the greatest effect on plant response (Grant et al., 2001). Early season P deficiency results in restricted plant growth, which the plant will not recover from, even when additional P is added later on (Froese et al., 2020). Therefore, there is considerable interest in how crops respond to P fertilizer placed in the same furrow as the seed, termed seed-row placed P, that is commonly used by growers to ensure early access of the crop to the P.

The supply of P to canola early on in the growing season via placement in the seed row is important in promoting increased root growth and early season vigor due to P being available for uptake by the seedling early on when it needs it (Grant & Flaten, 2019). Generally, the P fertilizer is applied in the prairies as granular monoammonium phosphate in the seed row at rates less than 25 kg P_2O_5 ha^{-1} in the seed row, as higher rates can cause damage to canola (Saskatchewan Ministry of Agriculture, 2019). The optimal application practice for canola is to seed-place at low rates that will not cause injury and to side or mid row band the additional P if its recommendation rate ranges from 30-50 kg P_2O_5/ha. Unlike N and S that are mobile in the soil, P is not as mobile, moving only a few mm from where it is placed, and needs to be placed close to the roots to maximize availability in the year of application (Havlin, 2014). As the roots grow outward, there may be advantage in having P placed further away from where the seed is to ensure continued root access and encourage outward root growth and exploration. A wider row spacing or a side-band system offers a good compromise in application strategy (S. P. Mooleki et al., 2010). However, a close side banding option is not always available to producers and depending on the seeding set up they use, they may only be able to place the P fertilizer in the seed-row with the canola seed, and/or in a band several cm away from the seed-row. However, phosphorus fertilizer can be toxic if concentration near the seed is too high. A high rate of seed row P fertilizer placement such as that exceeding 30 kg P_2O_5 ha^{-1} can cause potential salt injury to young seedlings of many crops (Qian et al., 2012) and canola is particularly sensitive to the salt effect of the fertilizer reducing germination and emergence.

The recommended seed-placed P fertilizer safe rates are 15 lb $P_2O_5 ac^{-1}$ (17 kg P_2O_5 ha^{-1}) in Alberta, 20 (22 kg P_2O_5 ha^{-1}) in Manitoba, and 25 (28 kg P_2O_5 ha^{-1}) in Saskatchewan. However, all of these rates cannot replace all the P that is removed in the grain of a high yielding canola crop. The current maximum safe rate of seed-placed P for Saskatchewan is based on 1" opener and 9" row spacing (~15 percent seed bed utilization) as provided in the Saskatchewan Ministry of Agriculture Guidelines for Safe Rates of Fertilizer Placed with the Seed. Increasing the spread of the fertilizer across the seed-row and narrowing row spacing increase seed-bed utilization (SBU). Thus, the average distance between fertilizer granules and seed is increased, resulting in the reduction of potential injury, and an increase in the allowable seed-row placed fertilizer. However, greater fertilizer spread may also affect plant availability of the P by increasing contact between fertilizer and soil components that are capable of fixing P through adsorption and precipitation reactions. Fertilizer spread can also influence root access to P in the rooting volume as the crop grows and develops. While some previous studies have examined maximum safe rates of P in the seed-row, there is little or no information on the relationship between opener width, row spacing, rate and the availability of the P fertilizer and crop response as revealed in crop P uptake and recovery of the added P fertilizer.

1.2 Justification of research

The P fertilizer monoammonium phosphate (MAP) is the dominant form placed in the seed-row by prairie producers, but new sources such as magnesium ammonium phosphate (struvite) based fertilizer extracted from wastewater streams have recently become available and are promoted as a more sustainable crop fertilizer choice in western Canada. Due to its lower solubility, struvite may behave differently from MAP in P availability and the crop responses produced in the season of application, as well as in the following crops in rotation. This is examined in this thesis research via a controlled environment study that compares yield, P uptake and recovery by canola followed by wheat and pea using MAP with struvite applied at different rates using two opener spreads as a typical prairie crop rotation.

While emergence and yield effects associated with greater rate of seed-row placed fertilizer under a single opener row spacing configuration have been evaluated in previous studies in a controlled environment (Qian et al., 2012), no studies have evaluated how opener spread and row spacing might affect the recovery and efficiency of utilization of the applied P fertilizer by the crop in the field at different rates of P fertilizer application. The spread and distribution of P fertilizer across the seedbed can potentially influence the degree of contact and fixation of the added fertilizer with soil constituents, and the ability of roots of the crop to access the P. The research in this thesis project addresses this gap in knowledge by determining the effect of opener spread and row spacing on canola yield and MAP P fertilizer uptake and recovery of fertilizer applied at five different rates ranging from 0 to 73 kg P_2O_5 ha^{-1}. The study was carried out at five field site locations in western Canada in the 2019 growing season. Both the controlled environment and field studies aim to improve our understanding of how P fertilizers may be managed when seed-row placed to optimize the crop response and P fertilizer use efficiency.

1.3 Hypothesis and Objectives

Considering the lack of information and gaps in knowledge identified above, the following hypotheses were developed for this thesis research:

1) Canola biomass yield and P uptake will be increased with addition of P fertilizer in the seed-row.

2) Struvite, a source of P fertilizer that is less soluble than MAP, will result in reduced yield and crop P utilization response compared to MAP. Response to both fertilizers will be affected by opener spread, rate and crop grown in rotation under the controlled environment conditions of the growth chamber.

3) Opener spread, row spacing, and rate of seed row placed P fertilizer will influence yield, P uptake and recovery by canola grown in the field. Treatment effects will be influenced by varying soil and environmental conditions encountered across the field sites and will be different from that observed under controlled environment conditions.

The major objectives of this study are as follows:

1) Assess how rate of P applied in the seed-row along with fertilizer form (MAP vs. struvite) and opener spread affect yield, P uptake and recovery by canola, wheat and pea grown in sequence under controlled environment conditions.

2) Determine the effect of MAP fertilizer applied at five rates in the seed- row under different opener spread and row spacing configurations (seed bed utilizations) on canola biomass yield, P uptake and recovery as influenced by soil type and environment in the field.

1.4 Organization of Thesis

The structure of this thesis includes chapters covering the research intended for publication. The first chapter provides the overall thesis introduction and justification for the research. Chapter 2 is a review of relevant literature with emphasis on soil P chemistry and P fertilizer management. Chapter 3 is the first research chapter and addresses the agronomic effects (biomass yield, P uptake, recovery) as affected by P fertilizer form (MAP, struvite) opener spread (narrow, wide) and rate treatments. Chapter 4 is the second research chapter addressing the agronomic effects as affected by P fertilizer treatment (MAP rate, opener spread, row spacing) under field conditions. Chapter 5 is a synthesis of the research, addressing the broader impacts of the findings, along with conclusions and suggestions for further research. Chapter 6 contains literature cited in this thesis. Additional ancillary data is provided in the Appendix.

2. Literature Review

2.1 Phosphorus in Soil

Phosphorus is one of the most important macronutrients for plant life as it plays a crucial role in energy storage and transfer, reproduction, and structure. The native plant available P in the soil comes originally from the weathering of P-rich primary minerals contained in the parent material (Brady and Weil, 2008). Phosphorus can also be added to the soil system as fertilizer, manure, or crop residue; it can be removed from the soil system through crop removal, erosion and runoff. Phosphorus can exist in soil in various forms including organic and inorganic forms; those P forms are different in their behavior and fate in soil (Condron, 2004). The organic forms of P comprise approximately 25% to 55% of total P content in soil, while inorganic P makes up about 35% to 75%. The availability of soil P is affected by soil properties and climatic conditions. For example, P mineralization and weathering rates are sensitive to climatic conditions such as temperature, moisture, and soil aeration. Warm, moist, well-aerated soil promotes root growth, decomposition processes and phosphorus release (Condron, 2004).

Organic forms of P in the soil include organic P in living roots and root exudates, plant residues, animal waste, soil biota, humified soil organic matter in solid phase and soluble organic P (Doyle and Cowell, 1993). The organic forms of P in soil are not directly available to plants as they have to be converted to the inorganic form by mineralization. Some microbes in the soil can metabolize the soil organic matter as an energy source. Also, mineralization of soil organic P can be catalyzed by plant roots and microorganisms, releasing phosphatase enzymes. In contrast, immobilization is the process in which soil organisms incorporate soil P into their biomass via metabolism. Together, immobilization and mineralization of P cycles the P through plant unavailable and available forms via tie-up when absorbed by soil organisms, and available P being released through biological decomposition and biochemical enzymatic activity. The balance between mineralization and immobilization is affected by biotic and abiotic conditions including type of plant residues, C:P ratio in the organic material, species of soil microorganisms, temperature, pH, and moisture conditions (Havlin, 2014).

The inorganic P forms in soil include soluble phosphate ions in the soil solution, P that is adsorbed on soil particle surfaces, and P that is precipitated as secondary and primary minerals (Havlin, 2014). These different inorganic P forms vary in availability. The phosphate ions in the soil solution are most available to plants, while P in insoluble primary minerals is the least available. Primary minerals such as apatite [$Ca_5(PO_4)_3(OH, F, Cl)$] are generally stable in soil due to very low solubility. They can dissolve and release P through weathering, but this is a very slow process that cannot supply crop with enough P in growing season (Mehmood et al., 2018). In contrast, there are secondary P minerals in the soil such as calcium, iron, and aluminum phosphates that are more available to crops depending on solubility. The P in secondary minerals cycle more rapidly than in primary minerals, dissolving and precipitating, cycling between labile and non-labile pools through a series of reactions. The reactions are affected by many factors including the size of the mineral particles, P or other anion concentrations in soil solution, soil pH, and the availability of metals like Ca and Mg that precipitate with P. Colloidal particles like clay and humus have a large surface area which create sites for inorganic P adsorption and desorption reactions. Soil pH influences the balance of those equilibrium reactions. Under acidic conditions, phosphate ions can precipitate with Fe and Al, while precipitation occurs with Ca and Mg under alkaline soil pH conditions (Havlin, 2014). For example, in acid soils, the solubility of the Fe and Al phosphate increases with increased pH; but Ca phosphates will have reduced solubility as pH rises above neutrality (Hinsinger, 2001). In alkaline calcareous Saskatchewan soils, for example, apatite and brushite are the most common Ca-P minerals as the soil parent material is enriched with Ca and carbonate. In comparison to apatite, brushite ($CaHPO_4 \cdot 2H_2O$) is more soluble and available to plants due to the different chemical constituents and structure.

Phosphorus that is directly available for biological uptake exists in soil solution as inorganic P, mainly as orthophosphate ions (Schachtman et al., 2016; Ullrich-Eberius et al., 1984). The chemical speciation of the orthophosphate ion existing in a soil environment is strongly affected by the soil pH, as it behaves as a weak Lewis base. Phosphoric acid has three pK_as: 2.12, 7.21, and 12.67; each number represents 50% dissociation of a proton at a given pH. As shown in Figure 2.1, primary orthophosphate ($H_2PO_4^-$) dominates in acidic soils while secondary orthophosphate (HPO_4^{2-}) dominates in basic soils.

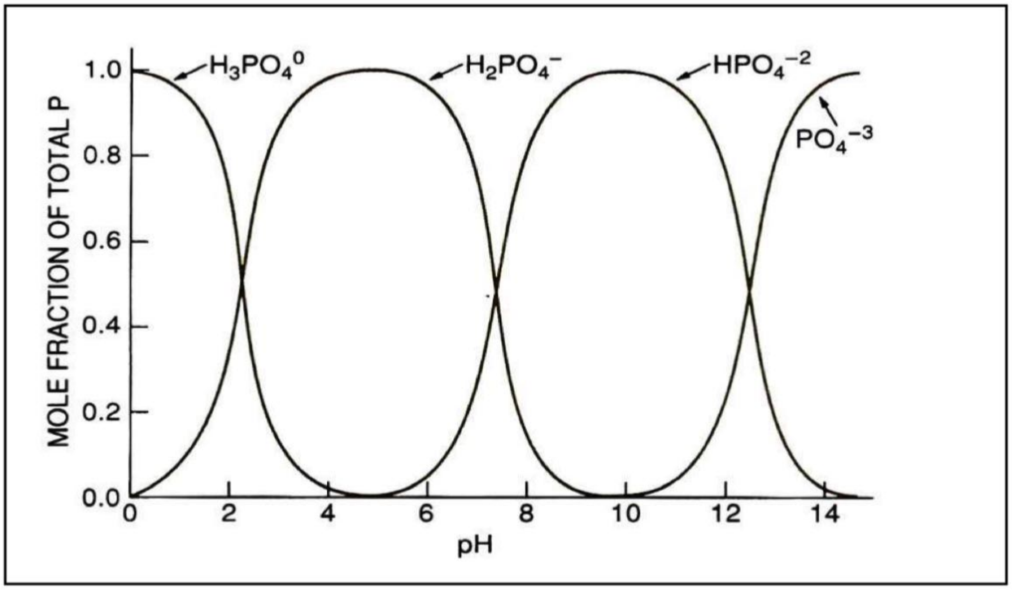

Figure 2.1: Speciation of orthophosphate as influenced by pH (Havlin et al. 2014).

2.2 Phosphorus Fertilization Management

2.2.1 P fertilizer availability

Adding fertilizer to soil is a common practice in agriculture. When water-soluble P fertilizer is added to the soil, the granule dissolves within a few hours or days, but only a small proportion of it stays in solution (Havlin, 2014). The dissolved P fertilizer from the granule rapidly undergoes a series of equilibrium reactions that reduce its solubility and therefore, availability to plants. Soluble P can adsorb onto the surface of soil colloids through outer sphere and inner sphere complex reactions. Also, soluble P fertilizer reacts with calcium and calcium carbonate minerals in calcareous soil; and react with Al and Fe oxides in acidic to neutral soil, all of which result in the formation of sparingly soluble P minerals (Holford, 1997).

In calcareous soil, P minerals are present in multiple forms including adsorbed PO_4 on carbonates, crystalline apatite, and poorly crystalline dicalcium phosphate minerals like brushite (Peak et al., 2012). Apatite found in long-term farmed soils has more stable crystalline structure in comparison to un-farmed soil; this could be caused by the application of phosphate fertilizer every year (Zhang et al., 2014). Enhanced formation of apatite reduces the mobility and availability of P in soil, as well as the P fertilizer use efficiency. Formation of apatite may be enhanced by greater contact of soluble P fertilizer with calcium in the soil. In soil containing high concentrations of Mg, dimagnesium phosphate trihydrate may also form. Both dicalcium phosphate dihydrate and dimagnesium phosphate trihydrate have lower solubility and mobility and therefore availability, compared to orthophosphate in soil solution. The reaction with Ca and Mg will continue over time, forming a compound with higher Ca/Mg to P ratio and lower solubility. Research has suggested that Mg ions can also inhibit the formation rate and crystallinity of the Ca-P at neutral to alkaline pH (Cao and Harris, 2008). With short and long term repeated application of liquid hog manure, which is dominated by struvite ($MgNH_4PO_4 \cdot 6H_2O$), an increased level of adsorbed P occurs with small amount of soluble brushite, and less apatite in comparison to solid cattle manure application (Kar et al., 2017). Therefore, although less soluble, the presence of Mg in struvite might reduce the longer term 'tie-up' effect of added P fertilizer by preventing or slowing the formation of crystalline apatite.

Due to low mobility of P and its fixation by reacting with minerals, roots cannot take up in a single season all the P that is applied as fertilizer, even under controlled environment conditions (Havlin, 2014). Therefore, it is important to consider the influence of soil residual available P on the following crop. Availability of residual fertilizer P is considered in detail in chapter 3 of this thesis. Moreover, environmental condition including soil moisture content can affect P availability through processes like sorption and desorption, microbial mineralization, and root growth and exploration, all of which are affected by pH, temperature, and moisture. For example, reduced soil moisture or drought can decrease inorganic P desorption, which directly reduces soil P availability (Dijkstra et al., 2015). Lower soil moisture levels increase the concentration of P in soluble or labile forms, which pushes the equilibrium toward the formation of P minerals that decrease P mobility and reduces the P uptake by plants. The importance of soil moisture on crop P uptake is discussed further in chapter 4 of this thesis.

2.2.2 4R Nutrient Stewardship

The 4R nutrient stewardship philosophy is to apply the right nutrient source at the right rate, right time, and right place to optimize agronomic crop yield and quality while minimizing nutrient losses to surrounding water and air. The 4R principles, as applied to P fertilizer management, are covered below.

Right source – choosing the right source means using the form of fertilizer that is suitable to the crop being grown, the time and place it is applied, and the environmental conditions in the field. P fertilizers available includes liquid fertilizer sources such as ammonium polyphosphates or dry granular fertilizers such as MAP, DAP, triple superphosphate (TSP), rock phosphate, struvite, and combination products like ammonium phosphate sulfates. The fertilizer selection must also consider factors like local soil characteristics. For instance, both MAP and DAP are highly water soluble and contain orthophosphate and ammonium that can improve P uptake, which makes them good sources of P. However, MAP is the most common form of phosphorus fertilizer used in the Northern Great Plains. The DAP produces a high pH around the granule when it dissolves in comparison to MAP and has a higher concentration of ammonium in comparison to MAP. The high pH produced by DAP reduces the P availability on neutral to high pH soils typical of the prairies and also increases the likelihood of injury from free ammonia in the seed row which makes MAP a more effective P source especially on calcareous soils (Grant and Flaten, 2019). Struvite has received relatively little attention on the Canadian prairies but some research in the growth chamber in Manitoba has shown struvite to be an effective P source for canola (Ackerman et al., 2013). This work showed similar P uptake by canola from MAP and struvite, but lower yields from the struvite that was attributed to lower initial solubility of the struvite following application. It has been suggested that banding may have reduced dissolution of struvite compared to mixing through the soil, since a low solubility P source like struvite may have improved performance when soil-fertilizer contact is increased, as proposed by Grant and Flaten (2019). However, no direct comparisons of fertilizer spread effects have been made previously and the current thesis research addresses this gap in Chapter 3. Other studies have reported greater seed safety and increased residual benefit to following crops in pot study evaluations of struvite compared to MAP (Katanda et al., 2016, 2019). The research in this thesis examines safety and residual benefit in a canola-wheat-pea rotation typical of the Canadian prairies.

Right rate – Phosphorus fertilization rate should ensure the crops have enough P that is required to optimize the crop growth. The right rate is affected by crop type, crop rotation, residual soil nutrient levels, and other factors including local climate and agricultural management. Moreover, the recommendation for P fertilization is commonly based on a short-term sufficiency strategy which is to supply just enough P to maximize the crop yield in the year of application; while a long-term sustainability strategy aims to manage the soil P level within a specific range, where the soil background P level is not limiting crop production and by replacing what is removed in crop harvest (Grant and Flaten, 2019). The phosphorus use efficiency (PUE) of applied P fertilizer is low, with the crop P uptake in the year of application rarely greater than 25% and often much lower (Syers et al., 2013). The effect of residual fertilizer P is discussed in chapter 3 of this thesis.

Right time – Early season P supply is critical to reach the optimum yield potential, so it is important for the seedling to get access to P in its early stages. In canola, for example, banding P fertilizer during the seeding operation will provide the crop with "jump-start" effect and the residual P will be located below the surface where it is protected from loss in erosion and runoff.

Right place –The best P fertilizer placement is influenced by aspects of source, rate, and timing as discussed above. A key consideration is the lack of mobility of P in the soil and the importance of early season P nutrition in annual crop production, so it is critical to ensure that sufficient available P is available to the seedling. Therefore, there has been much emphasis on placement of fertilizer P together with the seed in the seed-row (Grant and Flaten, 2019). Most importantly, applied P fertilizer must be in a position where the crop can have access to, and the fertilizer will not be lost from the system. Seed-row placed, or side-banding method ensure the crop roots can reach the fertilizer in early season, while surface placement in broadcast is generally considered inferior (Wiens et al., 2019). Considerations in fertilizer application strategies related to placement are most relevant to the work conducted in this thesis and therefore, covered in detail in the following section.

2.3 P Fertilizer Application Placement Strategies

Phosphorus based fertilizers are often recommended as starter fertilizers, which should be placed close to the seed and seedling roots for early access. Annual short-season crops grown in the Northern Great Plains need the P shortly after germination to promote early growth and development, especially in cool dry or wet soils where mobility and root growth are already restricted (Grant and Flaten, 2019). Phosphorus placement should be managed to optimize the nutrient availability to crop growth but also avoid injury and set-back. In addition to placement in the furrow with the seed, separate band and broadcast applications are common practices for adding granular P fertilizers to soil.

Broadcast applications are the simplest method of P fertilization, which is rapid and does not require highly specialized equipment. From an operational standpoint, the P fertilizer can be distributed uniformly through the soil volume if it is uniformly applied and well-incorporated, which is especially helpful when using a high rate of P fertilizer to build the background P level in soil. However, due to the low mobility of P in soil, broadcast P that is not incorporated may be stranded at the soil surface, and the starter supply to the seedling can be reduced as plant roots will not be in close proximity to the P source immediately after germination. Also, soluble P fertilizer on the soil surface can be environmentally harmful when it moves with run-off water into water systems (Wiens et al., 2019). On the other hand, band application places the fertilizer below the soil surface in a narrow zone. This band may be in the seed-row or in a separate band. Placing fertilizer in a band below the soil surface gives the crop an advantage in competing against weeds for P uptake (Blackshaw and Brandt, 2009) and the root uptake is enhanced by placement in moist soil. Early research in Saskatchewan showed no significant yield benefit in wheat with broadcast P application at 20 and 40 kg P_2O_5 ha^{-1} in the year of application; however, a positive result was found from banded P application (Campbell et al., 1996). Normally, the band applied P fertilizer will stay intact over several years unless the soil is disturbed by tillage. Placing the P fertilizer in a concentrated region can minimize the contact between the soluble P fertilizer and the soil, which reduces the adsorption and retention of the P fertilizer by the soil constituents. Therefore, banding can maintain the availability of P fertilizer longer than broadcast application (Fixen, 1992; Kar et al., 2012). However, if the band zone is large such as with a wide opener spread, increased contact between fertilizer and soil could result in reduced solubility and availability. Fertilizer products of low solubility like rock phosphate may benefit from enhanced fertilizer-soil contact and the agents responsible for solubilization (Grant and Flaten, 2019).

Although band application has better efficiency for supplying P fertilizer than broadcasting, highly concentrated P fertilizer near the seed can reduce germination and emergence through an osmotic salt effect. Also, the ammonium from MAP could lead to ammonia toxicity. Increased N to P ratio in fertilizer increases the risk of seedling damage. For instance, MAP is less damaging compare to DAP and blends of urea and MAP. Controlled release of P from coated P fertilizer can also be less damaging than uncoated P fertilizer at the same application rate (Qian & Schoenau, 2010). Also, moisture can reduce the degree of damage by diluting the fertilizer and lowering the concentration of P fertilizer in the soil solution near the seed.

Band application can be further divided into seed-row banding, side-banding, and mid-row banding. Side-banding and mid-row banding reduce the chance that the seed will contact P fertilizer, which protects the germinating seed from salt damage even at high application rates, provided separation is good. For seed-row placed fertilizer, SBU is used to describe the proportion of the seedbed over which the fertilizer has been spread. Seedbed utilization is calculated simply as opener spread divided by row spacing. Higher % SBU means that the fertilizer is more diluted than lower % SBU and therefore, greater allowance for a higher application rate. The SBU can be increased by increasing the width of the fertilizer band through using an opener with a wider spread (e.g., shovel) compared to narrower spread (e.g., knife), or reducing the row spacing. The recommended safe seed-row application rate is normally calculated based on SBU. The safe seed-row placed fertilizer rate is generally higher for cereals and lower for oil seeds and pulses. At the same application rate, wider spread can reduce the risk of salt damage because it is less likely for seed to get too close to a fertilizer granule with a wider spread.

2.4 Analytical techniques in assessing soil P

2.4.1 Plant available P in soil

Soil testing plays an important role in determining P fertilization rate. However, the type of soil test should fit the soil characteristics of a specific region. For example, the most common extraction method for labile soil P is the Olsen test, which uses sodium bicarbonate as a competitor to replace and dissolve slightly soluble P precipitates (Olsen et al., 1954). This method is an effective method for high pH, calcareous soils. The Bray or Mehlich test methods are designed for non-calcareous soils with neutral to acidic pH (McKenzie et al., 1995). In prairie provinces like Alberta and Saskatchewan, popular methods for assessing plant available P in the soil include the modified Kelowna extraction and ion exchange resin in membrane form (Plant Root Simulator [PRS^{TM}])).

As a chemical extraction method, Modified Kelowna (MK) was developed by Ashworth and Mrazek (1995) to provide a measurement of plant available P in the soil. The MK extraction is conducted at a pH that can neutralize the buffering capacity of the calcareous soil, which is a common soil type on the Canadian prairies. As well, the P extracted by MK was shown to have a strong positive correlation with the Olsen method, which makes MK a good substitute for the Olsen test (Qian et al., 1994).

Extraction with ion exchange resin membrane is another method that assesses P status using the membranes as a sink for the nutrient ions around the membrane during the period of extraction (Qian and Schoenau, 2002). Unlike in a chemical extraction method like MK, pH is not altered and the conditions under which P is extracted by the resin membrane more closely resemble the natural condition of the soil. A resin membrane within a plastic frame can be placed directly into the soil to measure the release rate of various nutrients in the soil over a specific time period. This type of resin is commercially available and known as Plant Root Simulator® (PRS^{TM}) probes. The resin membrane carries an electrostatic charge which attracts nutrient ions with opposite charge. The ion exchange resins used for this thesis are the resin membranes but without the frame. The MK and ion exchange resin membrane extraction methods were used to assess soil available P status at the end of the crop rotation evaluated and described in Chapter 3 of this thesis work.

2.4.3 P speciation

After P fertilization, plant available orthophosphate released into solution from granule dissolution will precipitate with cations like Ca present in the soil solution, thereby forming less available P minerals. Alternatively, it can be adsorbed on existing minerals. Different fertilizer sources may result in a different P mineral composition and/or level of adsorbed P.

Spectroscopic techniques are an effective approach to analyze P mineral composition. For example. X-Ray Absorption Near Edge Structure is a spectroscopic technique that measures energy released from atoms excited by x-ray, which is capable of differentiating P species in different oxidation states (Hesterberg et al., 1999; Peak et al., 2002). Moreover, adsorbed P at mineral-water interfaces plays an important role in determining the solubility and mobility of P (Hamilton et al., 2017). Attenuated total reflectance Fourier transformed infrared spectroscopy (ATR-FTIR) is another technique used in examining sorption mechanisms on mineral surfaces. Infrared spectroscopy is sensitive to differences in bonding environment, which makes it a good tool to examine the phosphate adsorption to minerals (Aufort et al., 2016; Liu et al., 2013). ATR-FTIR was used in this thesis work in an attempt to further identify the nature of residual P reaction products formed in P fertilizer amended soils.

3.0 Effect of Phosphorus Fertilizer Form, Opener Spread and Rate of Application on Biomass Yield, P Uptake and Recovery in a Canola-Wheat-Pea Rotation Under Controlled Environment Conditions

3.1 Preface

This chapter examines response of crop (canola, wheat, and pea grown in rotation) and soil to P fertilizer form, opener spread, and rate treatments added to the canola in the seed-row under controlled environment conditions. Crop emergence, 30 day above ground biomass yield, uptake of P and apparent recovery of fertilizer P are determined, along with labile soil residual P concentrations at the end of the rotation. The findings are discussed in relation to agronomic implications of P fertilizer type and placement strategies.

3.2 Abstract

Phosphorus fertilizers are widely used in production of small grains on the Canadian prairies. For canola, seed-row placement at the time of seeding is a common practice in Western Canada. Due to the greater yield and crop removal potential of modern canola varieties and the crops that follow in the rotation, the current P recommendation rate on the prairies is 25 - 30 kg P_2O_5 ha^{-1} placed in the seed-row, which may not be enough with canola. Opener spread influences the proximity of the seed and fertilizer placed together in the seed row as well as the degree of soil-fertilizer contact, and therefore may also affect crop response to P fertilizers. While monoammonium phosphate (MAP) is the most commonly used P source on the Canadian prairies, new P fertilizer forms have become available, including struvite produced by recycling P from wastewater streams. There is a need to consider how traditional and new P fertilizer sources interact with opener spread and rate to affect the response of canola, and the cereal or pulse crops that typically follow in rotation. Therefore, a controlled environment pot study was conducted using a P deficient Brown Chernozem soil collected from the field in the fall of 2018. Canola (*B. napus* hybrid var LL252), wheat (*Triticum aestivum* hard red spring var Brandon), and pea (*Pisum sativa* dry green var Stryker) were grown in rotation. The P fertilizer application in the rotation was made as seed-row placed P fertilizer applied to the canola at the beginning of the crop rotation. The P fertilizer treatments included 0, 20, 40, and 60 kg P_2O_5 ha^{-1} application rates placed in the seed-row using 1" and 3" opener spread, with two different P sources: MAP (11-52-0) and struvite (5-28-0, with 10%Mg). The application of P fertilizer at 20 kg P_2O_5 ha^{-1} significantly increased yield compared to the unfertilized control, while further rate increases produced no significant yield increases. Canola emergence measured 5 days after seeding decreased from about 95% in the control treatment to about 85% in the 60 kg P_2O_5 ha^{-1} rate, but the differences among rates were not significant and there was no significant effect of opener spread or P fertilizer form. The wheat grown following the canola had the highest yield at the 60 kg P_2O_5 ha^{-1} rate that was added to the previous canola crop. Overall, the 1" opener spread resulted in a better 30-day biomass yield, P uptake, and fertilizer P recovery in both canola and wheat compared to the 3" spread. Both MAP and struvite produced similar canola crop response in 30 days biomass yield, P uptake, and P fertilizer recovery while pea, as the third crop in the rotation, had no significant response to any treatment. These findings indicate that larger P

fertilizer applications to a canola crop than that required to maximize yield in the year of application, can be made with the intention of having the unutilized fertilizer P carry over and provide benefit to subsequent crops. The narrow opener spread (1”) performed better in canola yield response to added P and recovery of P fertilizer compared to the wide (3”) spacing and did not appear to reduce canola emergence even at the high rates of added P, despite closer proximity of seed and fertilizer. The struvite P fertilizer appeared to be a good alternative P source for canola with benefit to the following crop in the rotation also observed. Further evaluation of treatments under field conditions is desirable.

3.3 Introduction

Application of phosphorus fertilizer is critical in maximizing crop performance in western Canada. The supply of P to canola early on in the growing season via placement in the seed row is important in providing a ‘jump start’ effect, which refers to increased root growth and early season vigor due to P being available for uptake by the seedling early on. Generally, the P fertilizer is applied to crops on the prairies as granular monoammonium phosphate (11-52-0) in the seed row at low rates, as rates higher than 25 kg P_2O_5 ha^{-1} in the seed row can cause damage to sensitive crops like canola and peas (Saskatchewan Ministry of Agriculture, 2019). Unlike N and S that are mobile in the soil, P is not as mobile and needs to be placed close to the roots to maximize availability in the year of application. The side-band system offers a good compromise application strategy, where fertilizer is placed in a band about 1 inch to the side and 1 to 1.5 inch below the seed at the time of seeding (S. P. Mooleki et al., 2010). However, this close side banding option is not always available to producers and, depending on the seeding set-up they use, they may only be able to place the P fertilizer in the seed-row with the canola seed. However, fertilizer can be toxic if concentration near the seed is too high. A high rate of seed row P fertilizer placement such as that exceeding 30 kg P_2O_5 ha^{-1} can cause potential salt injury to young seedlings of many crops, including canola (Qian et al., 2012). Furthermore, while MAP is the dominant P fertilizer form placed in the seed-row by prairie producers, there are other sources, such as Crystal Green™ (5-28-0, with 10% Mg), which is a struvite (magnesium ammonium phosphate) mineral extracted from wastewater streams. This product has recently become available and promoted for use as a more sustainable crop fertilizer in Western Canada. This less soluble P form may behave differently than MAP under different opener spreads.

Limited research has been conducted on the Canadian prairies soil to determine the optimum rate and opener spread of fertilizer P for modern canola cultivars, which have high yield potentials and high P requirement (40-50 kg P_2O_5 ha^{-1}) (Katanda et al., 2019). MAP is the main P fertilizer used in western Canada, where the seed-row band application rate for MAP is not recommended to exceed 28 kg P_2O_5 ha^{-1} (25 lb P_2O_5 ac^{-1}) for canola in Saskatchewan. This rate, which is less than the P removal in grain of high yielding canola crops, may lead to soil P depletion and reduced yield of canola as well as the cereal and pulse crops that typically follow in rotation. Therefore, an experiment was conducted to assess how P fertilizer form (MAP vs. struvite), along with opener spread (i.e., 1” & 3”) and P rate (i.e. 0, 20, 40, 60 kg P_2O_5 ha^{-1})

affected yield, P uptake and recovery by canola grown on a P deficient Brown Chernozem soil under controlled environment conditions. Due to the immobility of P in soil, even under the controlled environment conditions, roots will not be able to take up all the P that is applied in a single season (Havlin, 2014). Therefore, wheat and pea were grown in sequence after the canola to examine the influence of residual fertilizer P in the soil. The available P remaining in the seed-row soil at the end of the canola-wheat-pea growth sequence was also determined using chemical and ion exchange resin extraction techniques.

3.4 Materials and methods

3.4.1 Soil description

The soil used was a P deficient Brown Chernozem soil of Ardill association collected from the field during the fall of 2018 from a pea stubble field. The complete soil analysis is provided in Table A-1. Briefly, the soil has loam texture, pH of 7.7, electrical conductivity (EC) of 0.25 dS/m (non-saline) in a 1:2 soil:water suspension and a modified Kelowna extractable soil test P concentration of 11 mg P kg^{-1} soil, which indicates deficiency in available P according to guidelines suggested for prairie soils (Grant & Flaten, 2019). Following collection from the field, the soil was air dried at room temperature and thoroughly mixed with a rotary soil mixer to ensure homogeneity.

3.4.2 Experimental design

Canola, wheat, and pea were grown in sequence in prepared soil trays to determine their responses to MAP and struvite P fertilizer sources applied in the seed-row furrow at four rates using two common opener spreads available to growers: 1” (narrow) and 3” (wide) under controlled conditions. The controlled environment facilities at the University of Saskatchewan College of Agriculture and Bioresources enable evaluation of emergence, early crop biomass production and P uptake response under controlled environmental conditions. The experiment utilized three crops (canola, wheat and pea) grown in sequence in order to provide a contrast in rooting system and crop P demand and which represents a typical oilseed-cereal-pulse crop rotation sequence used in Saskatchewan. Emergence counts were made 5 days after seeding and each crop was harvested 30 days after seeding to provide an assessment of the treatment effects on early season biomass yield and P uptake, since most of the P uptake by annual crops occurs early in the season and the benefits of seed-row placed P occur from enhanced early P nutrition (Grant & Flaten, 2019). Furthermore, it is difficult to get meaningful grain yields from canola that is grown in growth chambers. Grain yield data for canola, which is the main crop of interest in this thesis, is provided in a separate study conducted in the field described in chapter 4 of this thesis.

Elongated plastic trays divided into compartments each containing 5 kg of soil were used for the study. Seeding in the growth chamber was performed using 10 seeds per tray compartment to provide a plant density similar to that described in Qian and Schoenau (2010) for evaluating crop tolerance of canola to seed placed phosphorus fertilizers in a similar tray study. The soil surface was levelled to create a firm and even seed bed. A furrow was made in the middle of each experimental compartment using a seeding tool with two different hoe-type openers to create the desired opener treatment spread of 1” or 3” spread (opener furrow width), equivalent to 10% or 30% seedbed utilization. Fertilizer P at the appropriate rate was then evenly spread and distributed along the length and width of the furrow for each seed-row placed P fertilizer treatment. A total of 10 seeds were then evenly spread and distributed along the length and width of the furrow. Fertilizer and seed were then covered with approximately 2.5 cm of soil. Once the seeding was completed, the soil in the trays was maintained at 75% of field capacity throughout the 30-day growth period by daily watering with distilled water. Parameters in the GR 48 growth chamber used were a daytime day length of 18 hrs (from 6:00 AM to 12:00 AM) at 23 °C temperature, and night length of 6 hrs (from 12:00 AM to 6:00 AM) at 18 °C temperature.

One month (30 days) after seeding, the above-ground biomass of the plants in each experimental compartment was harvested by cutting the plants at the soil surface. For crop analysis, a sample of dried, above-ground plant material was taken and analyzed for total P concentration using acid digestion. Total above-ground plant P uptake for each crop was determined by taking the yield and multiplying by the P concentration. The recovery of P fertilizer added at the start of the experiment was calculated for each crop by taking the P uptake of the fertilized treatment minus the P uptake in the unfertilized control and dividing by the total amount of P added. The total recovery of P over the three-crop cycle was calculated by summing the total P uptake from all three crops. These measurements provide information on how P form, rate, and placement (opener spread) influence P availability, uptake and recovery in the canola crop to which the P fertilizer was applied, along with the following wheat and pea crops grown in rotation to enable assessment of residual benefits arising from the fertilizer P treatments made to the canola.

3.4.3 Canola with P fertilization

Canola (*B. napus* hybrid Invigor Liberty Link variety LL252) was grown in the U of S phytotron growth chamber facilities under controlled environment conditions in 2018. The experiment was set up as a completely randomized design (CRD) with four replicates of each treatment. The canola emergence, 30-days biomass yield, P uptake and apparent fertilizer P recovery was determined as a function of treatment. The treatments included two opener spreads at 1" (2.5 cm) and 3" (7.5 cm) width in which the canola seed was placed with P fertilizer. Two different P fertilizer sources as treatments were used: 1) Nutrien™ mono-ammonium phosphate MAP (11-52-0), and 2) Crystal Green™ struvite (magnesium ammonium phosphate: 5-28-0 with 10%Mg) added at 0, 20, 40, and 60 kg P_2O_5 ha^{-1}. There were four replications for each treatment. To duplicate fertilizer application as it would occur in the field, N and S was side banded 2.5 cm from the seed row and at 2.5 cm depth at 200 kg N ha^{-1} and 20 kg S ha^{-1}, respectively as urea and ammonium sulfate to eliminate any potential N and S availability limitations to growth.

The study was conducted using elongated plastic trays (73cm L x 16cm W x 16cm D), split into two separate compartments using sealed plastic divider inserts, with one treatment allocated randomly to each compartment in the group of trays. The trays simplify movement for watering and for frequent random repositioning within the chamber. The trays also enabled effective simulation of field seed-row fertilizer placement in rows and allowed for effective early root expansion horizontally and vertically. The soil trays were divided into two separate compartments using plastic board, sealant and duct tape, which isolated the compartments in terms of water, nutrients, and roots (Figure 3.1).

Figure 3.1: Canola growing in treatment trays in phytotron.

Compartments in the trays were each filled with 5 kg of soil per compartment. After filling, the surface of the soil in the compartments was gently rolled with a wooden roller to prepare the seedbed for seeding. The trays were completely randomized in their position and orientation on the growth chamber tables, and trays were re-positioned and re-randomized on the tables every two days when the trays were watered in order to account for any non-uniform environmental conditions across the growth chamber space.

3.4.4 Wheat and Pea Without P fertilization following Canola

Wheat (*Triticum aestivum* hard red spring wheat var AAFC Brandon) as shown in Fig. 3.2, followed by Pea (*Pisum sativa* dry green var CDC Stryker) as shown in Fig. 3.3 were grown in sequence in the same soil trays. After canola plants were harvested at 30 days after seeding, wheat was seeded, grown for 30 days and harvested, followed by seeding of peas and harvesting after 30 days., The wheat and pea crops were seeded in the same rows (1” and 3” spread) as the canola. For wheat, while P fertilizer was not added, N and S were side banded at the rate of 200 kg N ha^{-1} and 20 kg S ha^{-1}. For pea, no additional fertilizer was added, but all seeds were inoculated with *Rhizobium leguminosarum* before seeding to promote biological nitrogen fixation.

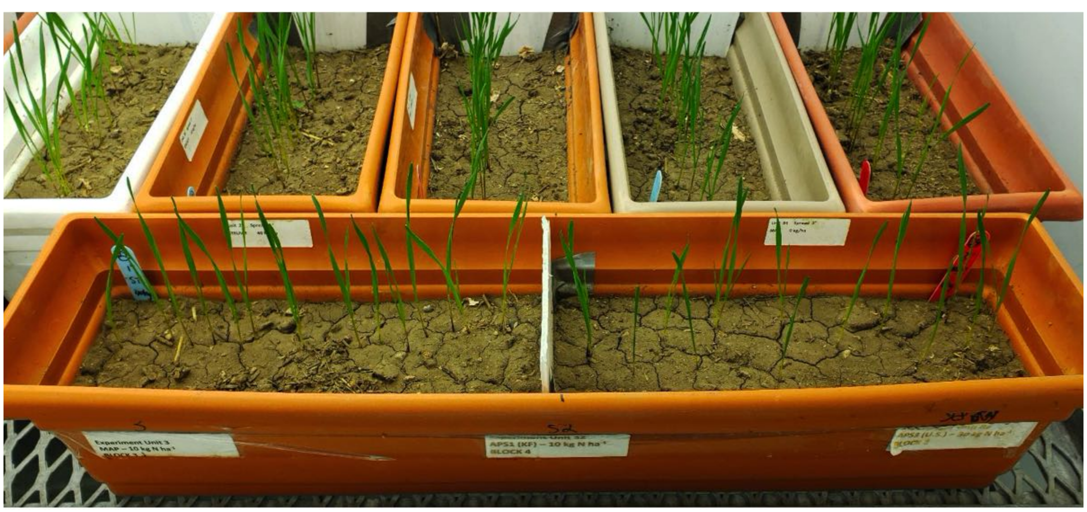

Figure 3.2: Wheat growing in trays following canola in phytotron study.

Figure 3.3: Pea growing in trays following wheat in phytotron study.

For each crop, germination counts were made 5 days after seeding. After 30 days, the above-ground biomass was harvested and dried at 60 ^{o}C in the University of Saskatchewan College of Agriculture and Bioresources phytotron drying room for 7 days. When all samples were completely dried, the samples were weighed to determine 30-day biomass dry matter yield. Then the dried plant material samples were ground into fine powder using a Udy^{TM} cyclone grinder mill, and mixed and subsampled for the sulfuric acid peroxide nutrient digestion described in the following section. There was a total of 192 samples: 3 crops x 2 opener spreads x 2 types of fertilizer x 4 rates x 4 replications.

3.4.5 Plant analysis

Above-ground crop samples were analyzed for P concentration by grinding followed by using a hot sulfuric acid-peroxide digestion (Thomas et al., 1967). In this method, 0.2490 - 0.2509 g of ground sample were weighed and transferred into a digestion tube followed by the addition of 5 mL of concentrated sulfuric acid (18M). The solution was then heated to 360 ^{o}C for 30 min with a heating block. Then, the tubes were removed from heating block and allowed to cool for 20 min. Once the tubes cooled to room temperature, 0.5 mL of 30% w/w H_2O_2 was added to the tube and vortexed. The solution was then heated on the heating block for another 30 min. These steps were repeated until the solution became clear (approximately 6 times).

When the solution was colorless, 0.5 mL of 30% w/w H_2O_2 was added to the tube one last time and heated on heating block for 60 min to remove the remaining H_2O_2. Once the solution had cooled to room temperature, the tubes were filled to volume marker (75 mL) using DI water. The tubes were then capped and inverted to homogenize the solution. The final extract was analyzed using automated ammonium molybdate blue colorimetry on a SEAL^{TM} autoanalyzer. Total above ground plant P uptake for each crop was determined by taking the yield (g) and multiplying by the P concentration in the plant (µg P g^{-1}).

3.4.6 Soil analysis

The soil used was a Brown Chernozem soil of Ardill association collected from the 0-10 cm depth of a farm field (pea stubble) with a history of low rates of P fertilizer application. The soil was collected using a tractor mounted front end loader in October of 2018 following pea harvest. The soil collected was dried at 30°C, mixed and homogenized and a representative soil sample obtained by taking 15 sub-samples from the mixture and bulking them. A soil analysis was conducted immediately on the sample at ALS Environmental Labs in Saskatoon. Available soil P assessments were also conducted at the end of the phytotron experiment after the pea was harvested to investigate the residual P present in soil. In the residual available soil P assessment at the end of the rotation sequence (following pea harvest), soil microcores (6 microcores of 2 cm in diameter to a depth of 5 cm) were taken at random from the seed/fertilizer row of each treatment replicate and bulked to provide a single sample representing each treatment replicate (total of 64 soil samples). Soil residual available P was determined using Modified Kelowna extraction and Anion Exchange Membrane techniques, described in the following sections. An attempt to provide further characterization of residual P forms present in the soil as a function of P fertilizer treatment was made using ATR-FTIR spectroscopy.

3.4.6.1 Modified Kelowna Extraction

A Modified Kelowna extraction was performed on soil samples after pea was harvested. In this method, 30 mL of MK solution (0.025 M HOAc, 0.015 M NH_4F, and 0.25 M NH_4OAc) was added to 3 g of air-dried soil. The suspension was shaken at 142 rpm for 5 minutes and filtered through VWR 454 filter paper (Qian et al., 1994). The extraction solution was then measured for orthophosphate P content using automated molybdate blue colorimetry on a SEAL Autoanalyzer®.

3.4.6.2 Anion Exchange Membrane P

An anion Exchange Membrane or "sandwich" P extraction method as described by Qian and Schoenau (2002) and using Qian et al. (2008) modification, was employed to measure exchangeable orthophosphate soil P.

In this method, anion exchange resin membrane strips were placed in a 0.5M $NaHCO_3$ solution and shaken for 2 hrs. This procedure was repeated four times with fresh solution between each interval for a total of 8 hrs. The membrane strips were then placed in DI water until use. Soil cores collected from each tray were sieved to < 2mm diameter and a small amount of the soil was used to fill each of two7-dram vial lids to form a small mound above the cap line, to ensure good membrane to soil contact. The soil in each cap was brought to field capacity with DI water on an analytical balance. A charged anion strip was placed on one soil-filled cap and covered by the other one, and wrapped by Parafilm®, which created the "sandwich" and enables the exchange of bicarbonate ions on the membrane surface with labile, exchangeable soil orthophosphate ions in contact with, and in the immediate vicinity, of the membrane . After 24 hrs, the sandwiches were unwrapped and soil that was adhering to the membrane was washed off with DI water. The membrane strips were then placed into a 7-dram vial and eluted with 20 mL of 0.5 M HCL for 60 mins. The membrane strips were then removed, and the eluting solution was measured for orthophosphate ions using SEAL™ automated colorimetry.

3.4.6.3 ATR-FTIR Spectroscopy

The ATR-FTIR measurements were conducted on a BRUKER INVENIO R spectrometer equipped with a N_2 cooled detector. Pure apatite, brushite, and struvite minerals were measured first as references. Soil collected from the seed-row of selected treatments: control (no P fertilizer) and MAP, and struvite applied with 1" spread at 60 kg P_2O_5 ha^{-1}. As well, soil samples with concentrated MAP and Struvite (fine grind) application (500 ppm) were prepared. Both reference minerals and soil samples were fine ground before the measurement.

3.4.7 Key calculations

The equations used to calculate crop (e.g., canola) P uptake, crop P recovery, and total P recovery are provided below. Note that the control is the comparable placement and fertilizer type treatment without P fertilizer added.

P uptake = crop P concentration x crop above-ground biomass

Individual crop (e.g., canola) P recovery = $\frac{treatment\ P\ uptake - control\ P\ uptake}{P\ application\ rate}$

Total P recovery (canola+wheat+pea) = $\frac{treatment\ P\ uptake\ (Canola+Wheat+Pea) - \ control\ P\ uptake}{P\ application\ rate}$

3.4.8 Statistical analysis

The statistical analyses were conducted using RStudio (ver. 1.2.1335) software. A multi-factor ANOVA was conducted with the means separated by Tukey-HSD test at $\alpha=0.05$ Outliers were detected using Grubbs test and removed. Specific information on which samples were removed can be found in the appendix (Table A-2).

3.5 Results

3.5.1 Crop yield, P uptake and recovery responses to treatments

Fertilizer type (MAP, struvite) did not have a significant (*$\alpha=0.05$*) effect on the first crop canola biomass yield and P uptake but had a significant effect on the following wheat crop (Table 3.1). The last crop, pea, was not significantly affected by treatments. Application rate of P fertilizer significantly affected biomass yield and P uptake in canola and wheat but not pea. Opener spread significantly affected biomass yield in all three crops and P uptake in pea and canola. Opener spread and its interaction with application rate were significant for canola P uptake and wheat 30-day biomass yield. The calculated % recovery of added P fertilizer in the above-ground biomass was significantly affected only by opener spread for canola, which received the P fertilizer as the first crop grown. The proportion of P fertilizer added to the canola crop that was recovered in all crops in the sequence (canola plus the following wheat and pea crop = total P recovery) was significantly affected by fertilizer type at $\alpha = 0.05$. (Table 3.1).

Table 3.1: ANOVA summary table of canola, wheat, and pea crop parameters collected from 2019 growth chamber study. Reported values are p values.

Crop	Treatment	Parameter			
		Biomass	Uptake	P Recovery	†Total P Recovery
Canola	Fertilizer	0.1281	0.8316	0.9065	**0.0047***
	Spread	**0.0006***	**0.0002***	**0.0153**	0.0986
	Rate	**0.0001***	**0.0001***	0.1289	0.1356
	Spread*Fertilizer	0.3046	0.8691	0.1737	0.2898
	Fertilizer*Rate	0.2407	0.9567	0.8408	0.6063
	Spread*Rate	0.0765	**0.0188**	0.6256	0.8532
	Spread*Fertilizer*Rate	0.2654	0.3915	0.1778	0.3329
Wheat	Fertilizer	**0.0017**	**0.0001***	-	-
	Spread	**0.0001***	0.1260	-	-
	Rate	**0.0001***	**0.0001***	-	-
	Spread*Fertilizer	0.4859	0.8330	-	-
	Fertilizer*Rate	0.386	**0.0001***	-	-
	Spread*Rate	**0.0001***	0.4230	-	-
	Spread*Fertilizer*Rate	0.7091	0.7520	-	-
Pea	Fertilizer	0.8233	0.0826	-	-
	Spread	**0.0094**	**0.0218**	-	-
	Rate	0.9939	0.9205	-	-
	Spread*Fertilizer	0.9569	0.6501	-	-
	Fertilizer*Rate	0.6937	**0.0983**	-	-
	Spread*Rate	0.9327	0.6076	-	-
	Spread*Fertilizer*Rate	0.9453	0.9850	-	-

† Total % recovery of P fertilizer applied calculated by summing P recovered by canola, wheat, and pea. *P-value* < 0.01 denote highly significant differences; *p-value* < 0.05 denote significant differences, and *P-value* > 0.05 denote non-significant differences. Significant *p-values* are bolded.

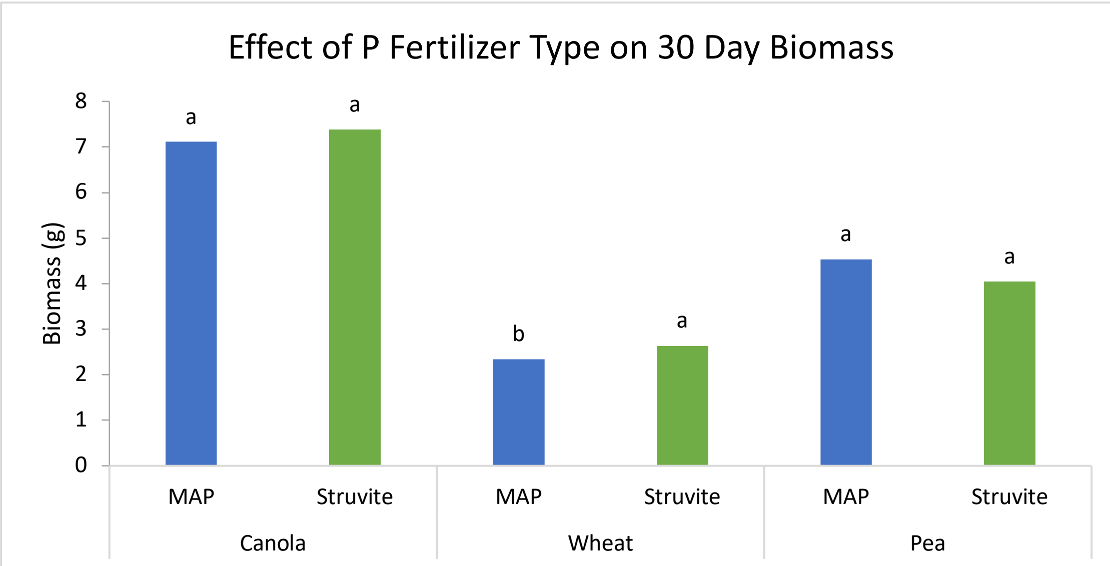

Figure 3.4: Aboveground biomass yield (g) of canola followed by wheat and pea in response to P fertilizer type applied to the canola in the phytotron. Means were separated using Tukey`s HSD test (α = 0.05). For a crop, bars with different letters indicate significant difference.

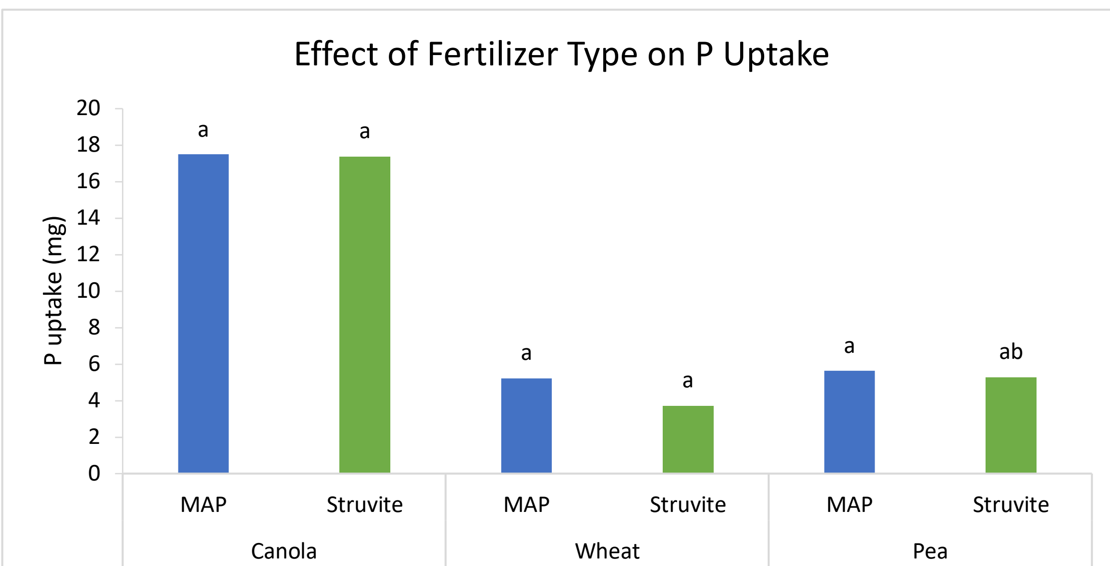

Figure 3.5: Crop P uptake (mg P) in response to fertilizer P type applied to canola in the phytotron. Means were separated using Tukey`s HSD test (α=0.05). For a crop, bars with different letters indicate significant difference.

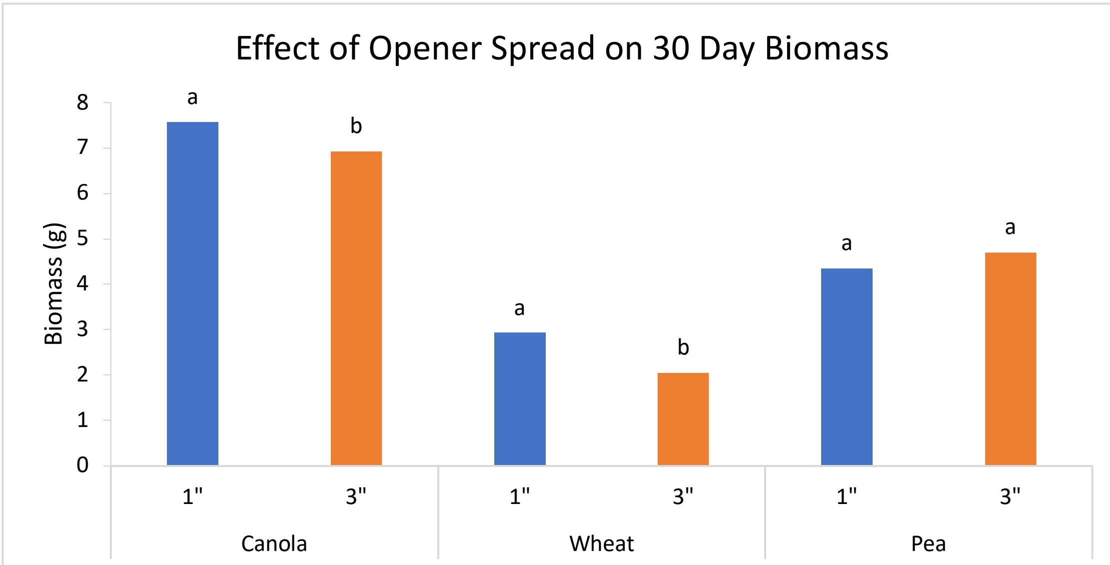

Figure 3.6: Above-ground biomass yield (g) of canola followed by wheat and pea in response to two different opener spreads used to apply P fertilizer to the canola crop in the phytotron. Means were separated using Tukey`s HSD test (α = 0.1). For a crop, bars with different letters indicate significant difference.

The MAP and struvite performed similarly in their effect on canola biomass and P uptake (Figures 3.4 and 3.5). The effect of fertilizer type is more pronounced in wheat as the second crop in rotation, where struvite resulted in slightly, but significantly greater biomass yields. However, MAP resulted in slightly higher P uptake (Figure 3.5). Pea did not significantly respond to fertilizer type when means were compared with Tukey`s HSD test at alpha = 0.05. However, the MAP fertilizer resulted in a numerically greater P uptake in pea.

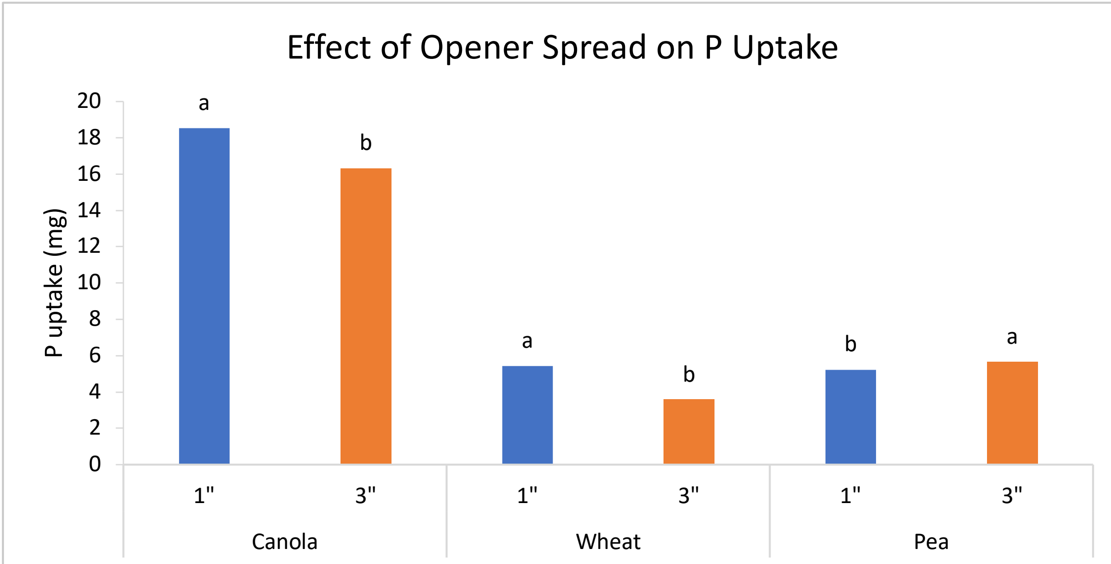

Figure 3.7: Crop P uptake in response to opener spread used to apply P fertilizer to canola. Means were separated using Tukey`s HSD test (α=0.05). For a crop, bars with different letters indicate significant difference.

Differences in opener spread significantly affected all crops in their 30-day aboveground biomass yield and P uptake response, except for the biomass yield of pea (Figure 3.6 and Figure 3.7). The 1" opener resulted in a greater yield and P uptake for canola and the following wheat crop. However, for pea, the last crop in the rotation sequence, the 3" spread produced slightly greater P uptake, which might be due to a shallower and more spreading nature of the pea root system.

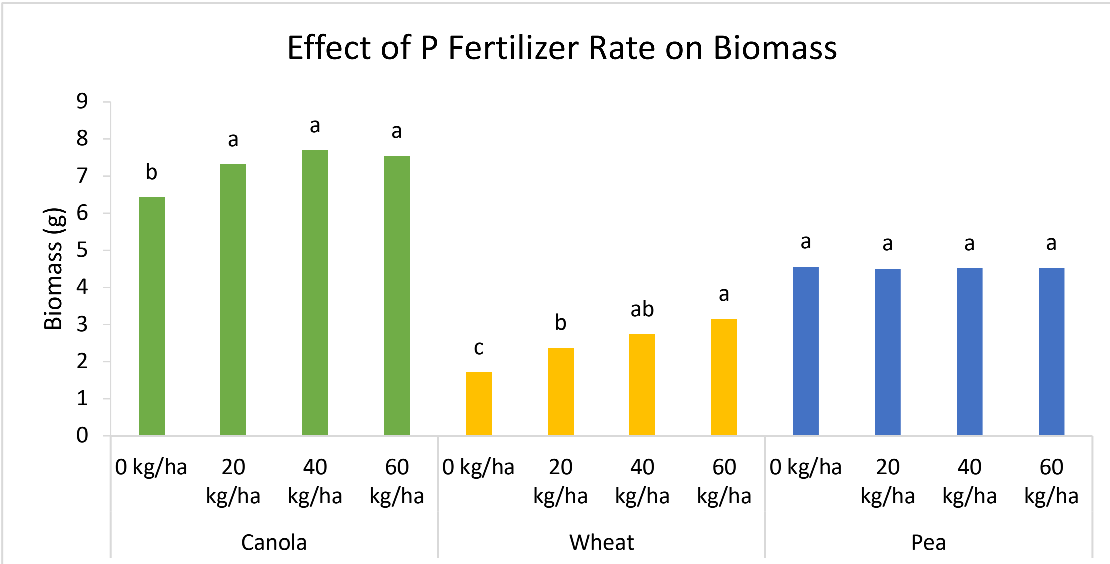

Figure 3.8: Above-ground biomass yield (g) of canola followed by wheat and pea in response in response to rate (kg P_2O_5 ha^{-1}) of P fertilizer (MAP and struvite yield data combined) applied to canola crop in the phytotron. Means were separated using Tukey`s HSD test ($\alpha = 0.05$). For a crop, bars with different letters indicate significant difference.

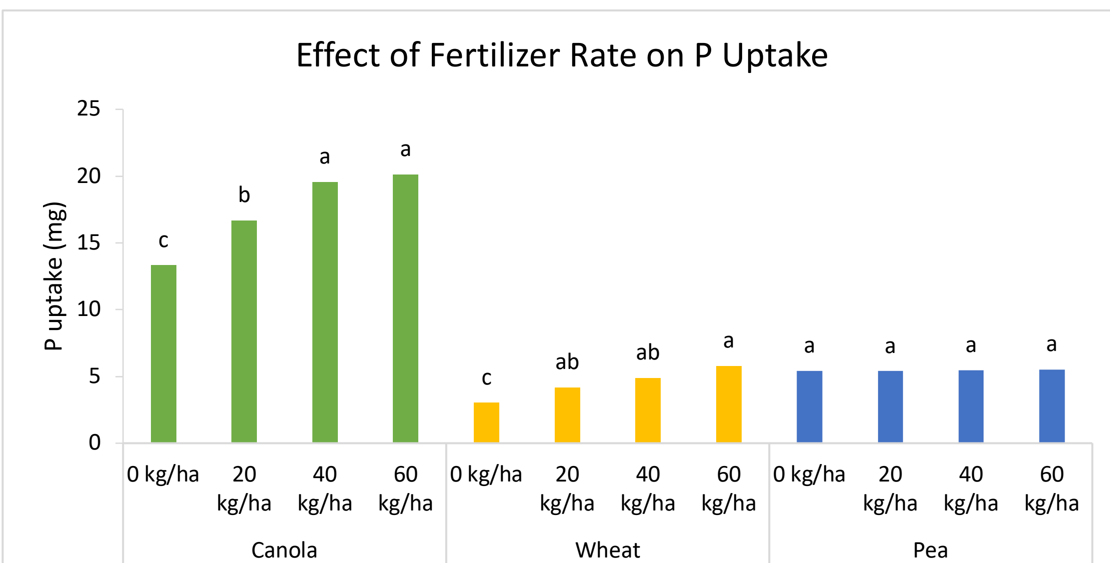

Figure 3.9: Crop P uptake (mg P) in response to P fertilization rate (kg P_2O_5 ha^{-1}) applied to canola. Means were separated using Tukey`s HSD test (α=0.05). For a crop, bars with different letters indicate significant difference. Error bars are standard error of the mean.

Phosphorus fertilizer application rate significantly affected yield and P uptake by the P fertilized canola and the following wheat crop (Figure 3.8 and Figure 3.9). In canola, addition of 20 kg P_2O_5 ha^{-1} significantly increased canola biomass yield above the unfertilized control. Canola biomass yield at rates of 40 and 60 kg P_2O_5 ha^{-1} were not significantly different from 20 kg P_2O_5 ha^{-1}. The highest canola yield was produced at 40 kg P_2O_5 ha^{-1} . The crop P uptake was more responsive to P fertilization than biomass yield, with 40 kg P_2O_5 ha^{-1} resulting in significantly higher P uptake by canola than lower rates. Increasing P uptake beyond the point of maximum yield may be considered luxury uptake. Highest mean P uptake of canola was achieved at the highest rate of 60 kg P_2O_5 ha^{-1}. Wheat was responsive to the residual P fertilizer left after the canola crop, with significantly higher 30 days biomass yield and P uptake at 60 kg P_2O_5 ha^{-1} rate (Figure 3.8 and 3.9) compared to lower rates. Pea, as the crop grown following wheat and canola, did not respond in biomass yield or P uptake to the P fertilizer application rates made to canola. This may reflect depletion of soil P by the previous crops as well as peas being good scavengers of soil P.

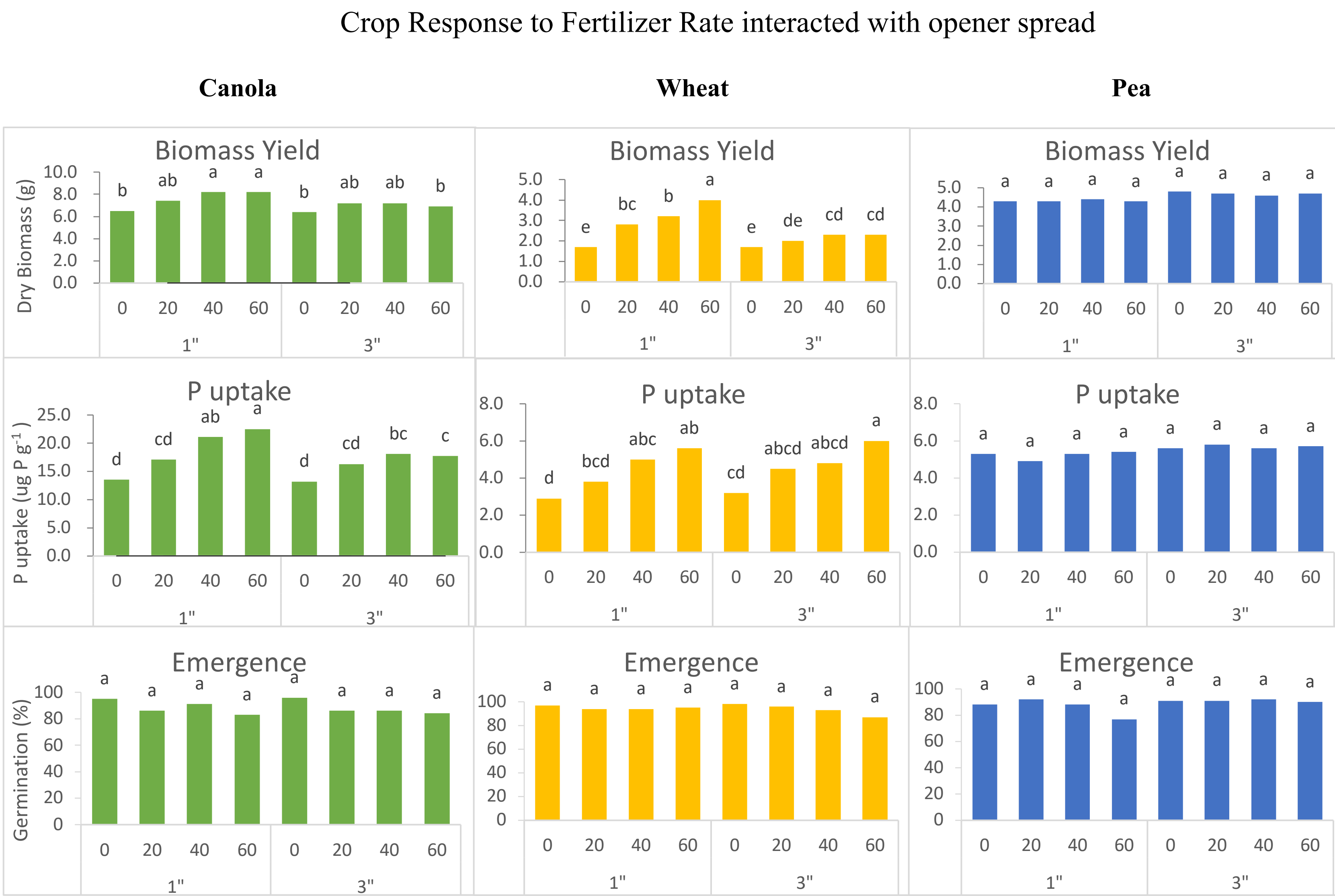

Figure 3.10: Effect of fertilization rate and its interaction with opener spread on 30-day crop biomass yield and P uptake, and emergence after 5 days. For a crop, means in a column followed by the same letter are not significantly different based on Tukey`s HSD test at α = 0.05 level of significance

Canola and wheat had significant responses to opener spread width, and its interaction with P fertilization rate (Figure 3.10). The narrower 1” opener spread with 60 kg P_2O_5 ha^{-1} rate of fertilizer application resulted in a significantly higher biomass yield and P uptake response in both the canola and wheat crop. In canola, the fertilization rate of 40 and 60 kg P_2O_5 ha^{-1} resulted a similar 30 days biomass yield and P uptake, while 60 kg P_2O_5 ha^{-1} fertilization rate resulted significantly greater 30 days wheat biomass yield over the rate of 40 kg P_2O_5 ha^{-1}. Pea, the third crop in the crop rotation, did not show any significant response to the treatments (Table A-5). Increasing P fertilizer rate resulted in a trend of lower mean emergence with increasing rate. This was observed for all crops including the canola to which the P fertilizer was added to the seed row, as well as for the following wheat and pea crops to which no P fertilizer was added and the crops were seeded into the seed row of the previous crop. However, the effects on emergence were not significant at $p = 0.05$ for any of the treatments (rate, spread, P fertilizer type). The higher P uptake with the 1” spread versus the 3” spread, which was significant at the highest P rate, may be explained by reduced soil-fertilizer contact and interaction, reducing fixation by adsorption and precipitation reactions.

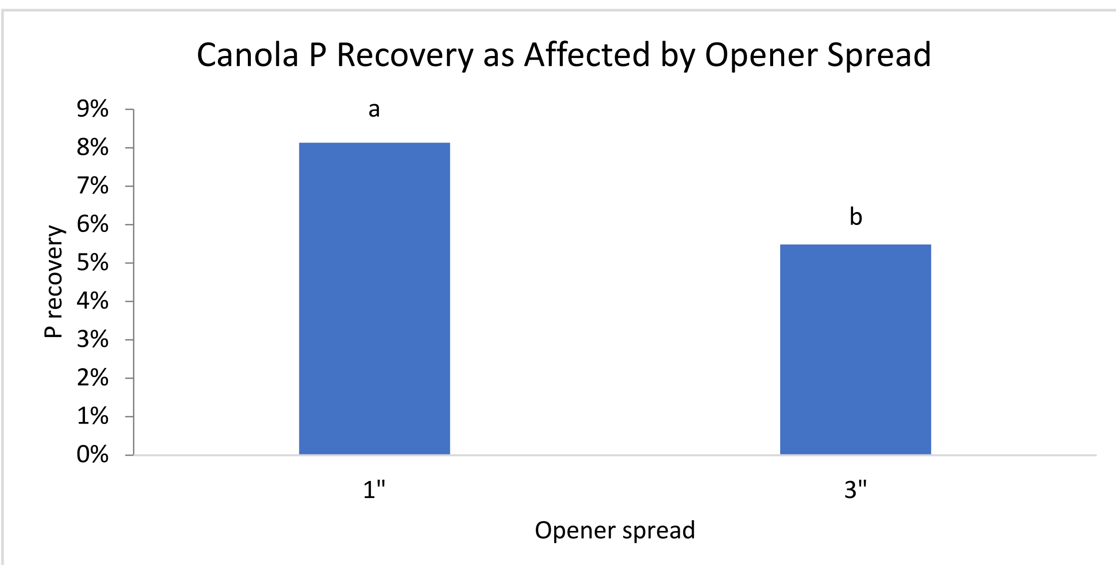

Figure 3.11: Canola P recovery (% of P fertilizer applied to canola present in above-ground biomass after 30 days) in response to opener spread. Means were separated using Tukey`s HSD test (α=0.05). Bars with different letter are significantly different.

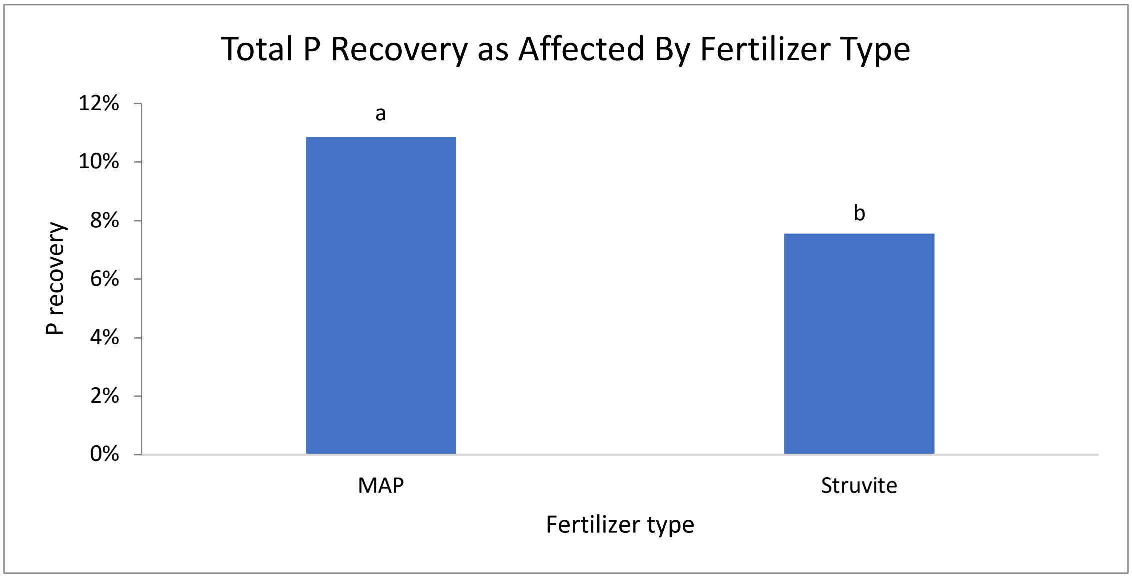

Figure 3.11: Total P recovery (% of P fertilizer applied to canola recovered in above-ground biomass of canola +wheat + pea crops after 30 days) in response to fertilizer type. Means were separated using Tukey`s HSD test (α=0.05). Bars with different letter are significantly different.

In the canola crop to which the fertilizer P was applied, opener spread is the major variable that affects the apparent P recovery (Figure 3.10), where 1” spread resulted in significantly higher P recovery compared to 3” opener spread (Figure 3.11). For P fertilizer added to canola crop that was recovered in all three crops grown (canola plus the following wheat and pea crops) the only significant response was to fertilizer type, where MAP resulted in slightly, but significantly greater apparent total P recovery compared to struvite (Figure 3.12). This may reflect greater solubility of MAP fertilizer reaction products in soil compared to struvite.

3.5.2 Residual soil phosphorus

Both soil available P assessment methods (Modified Kelowna and Ion Exchange Resin) showed similar treatment effects, where residual plant available P in the soil is significantly affected by fertilizer type, application rate and their interaction (Table 3.2). Both assessment methods indicate residual soil available P increased with increasing P fertilization application rate (Table 3.3). This suggests that fertilizer P applications made to the canola (first crop in the rotation) would provide subsequential crop with residual benefit in enhanced soil P availability, especially at higher rates. As well, both assessments show that at higher application rates above 20 kg P_2O_5 ha^{-1}, there is significantly less residual available P in the soil with struvite P form than with MAP. At high application rates such as 40 and 60 kg P_2O_5 ha^{-1}, greater amounts of P fertilizer applied at the beginning of the rotation remained unutilized, thus increasing the opportunity for P to convert to less soluble forms. The lower residual available P observed with struvite at the higher rates cannot be explained by greater plant uptake and removal but may reflect presence and/or formation of less soluble reaction products from struvite in the soil compared to MAP.

Table 3.2: ANOVA summary table for residual soil available P assessments made at the end of the phytotron study after pea harvest. Reported values are p value.

	Available P Assessment	
Treatment	**Kelowna P**	**Ion Exchange Resin**
Spread	0.5327	0.3236
Fertilizer	**0.0004**	**0.0055**
Rate	**0.0001**	**0.0001**
Spread*Fertilizer	0.8919	0.6709
Spread*Rate	0.6289	0.8399
Fertilizer*Rate	**0.0007**	**0.0125**
Spread*Fertilizer*Rate	0.9420	0.4948

Bolded number indicates *p-value* < 0.05

Table 3.3: Effect of fertilizer type and its interaction with application rate on residual soil available P assessments made at the end of the phytotron study after pea harvest. Means in a column followed by the same letter are not significantly different based on Tukey`s HSD test at α=0.05 level of significance.

		Assessment Method			
	Rate	**Kelowna** P		**Ion Exchange Resin**	
Fertilizer	kg P_2O_5 ha^{-1}	mg P kg^{-1}		ug cm^{-2} 24 hr	
MAP	0	5.2	d	0.020	c
	20	6.9	cd	0.034	c
	40	12.7	b	0.194	ab
	60	21.5	a	0.291	a
Struvite	0	5.0	d	0.028	c
	20	7.2	cd	0.044	c
	40	10.3	bc	0.093	bc
	60	12.4	b	0.123	bc

3.5.3 P speciation

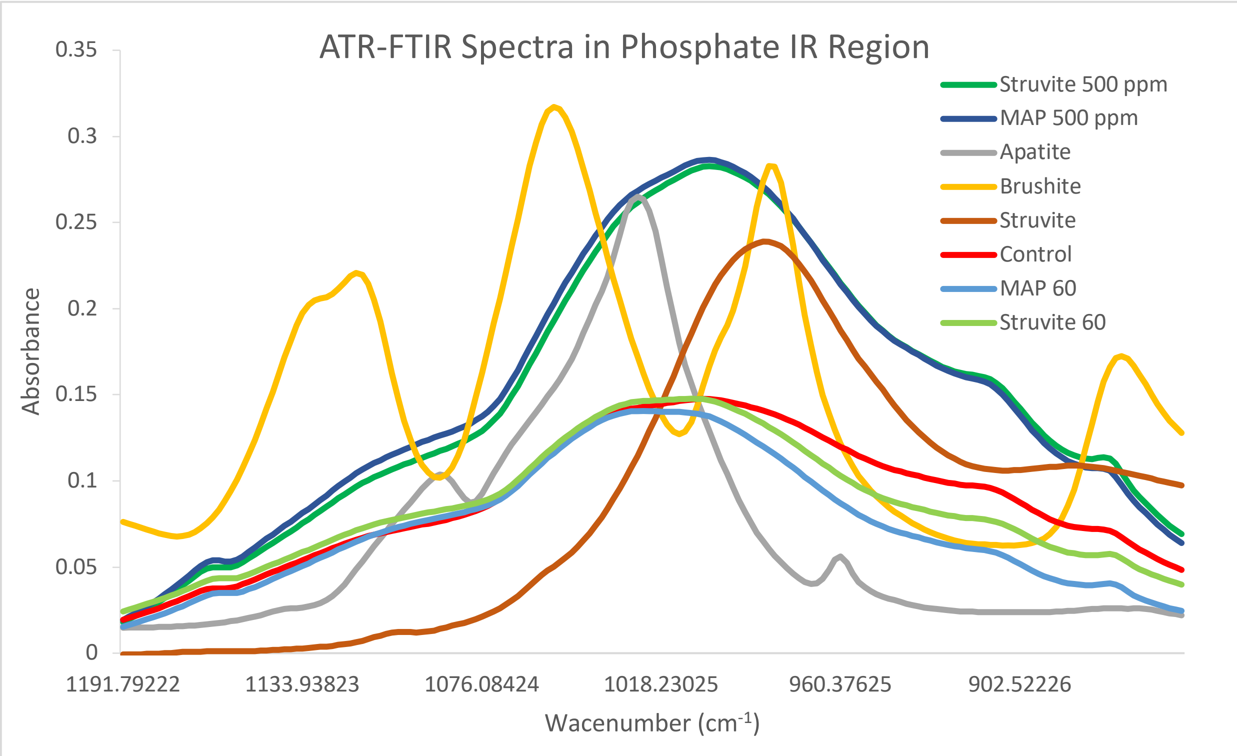

Figure 3.12: Comparison of ATR-FTIR spectra of prepared samples in phosphate IR region. MAP 60 and Struvite 60 represent soil samples collected from the seed-row of the tray study at the end of the cropping sequence with 60 kg P_2O_5 ha^{-1} fertilization rate applied to the canola. Apatite, Brushite and Struvite represent standard reference materials. Struvite 500 ppm and MAP 500 ppm are concentrated applications of the fertilizers to the soil used in the study.

Samples with concentrated P fertilizer application (Struvite and MAP at 500 ppm) showed greater absorbance in comparison to soil samples collected from the tray study, and there was no difference between MAP and Struvite concentrated fertilized soil samples (Figure 3.12). Unfortunately, the spectra of soil samples did not show characteristics that would be indicative of the presence of target minerals (apatite, brushite, or struvite). This might be due to background interferences in in the soil sample matrix that interferes with the spectrum reading. The soil samples with 60 kg P_2O_5 ha^{-1} equivalent P fertilizer rates added previously in the tray study did not clearly differentiate from the unfertilized control, suggesting that the differences in the samples were too small and below the detecting limit of the ATR-FTIR spectrometer.

3.6 Discussion

Canola, wheat, and pea were grown in sequence in order to provide a contrast in rooting system and crop P demand and to represent a typical oilseed-cereal-pulse crop rotation sequence in Saskatchewan. Different crops have different requirements for P and different ability to use soil P. Depending on the crop type and growth conditions, plants may increase root development, exude organic acids, or establish associations with mycorrhizal fungi to improve access to P (Havlin, 2014). Therefore, the crop yield response to P fertilizer application will depend on the amount of P required by the plant related to yield potential, its ability to access P from soil that is affected by root characteristics and microbial relationships, and the ability of the soil to supply P to roots in the amounts and time that the P is needed. Rate, placement, form and time of fertilizer P application (4 R's) need to be considered as this affects the success of the P fertilizer application in providing the supplemental P that the crop needs. These are considered in more detail below.

3.6.1 Crop response to fertilizer rate

In the controlled environment growth chamber study conducted as part of this thesis research, canola showed a significant 30-day biomass yield response to P fertilization at the 20 kg P_2O_5 ha^{-1} rate, while further rate increases produced no further significant yield increases. Mean canola biomass yield was maximized at the 40 kg P_2O_5 ha^{-1} rate. The rate response observed in this study is corroborated by results reported by others in the literature. A four-year field study in Manitoba found canola yield to be optimized at 24.7 kg P_2O_5 ha^{-1} (22 lb P_2O_5 ac^{-1}) (Grant et al., 2009). McKenzie et al., (2003) noted the most profitable P fertilization rate was between 10–20 kg P_2O_5 ha^{-1} for canola. As canola is sensitive to seed-row placed P fertilizer, a high rate of MAP, for example above 30 kg P_2O_5 ha^{-1} rate, can lead to seedling damage and yield reduction (Bailey & Grant, 1990; Grant, 2013; Grenkow, 2013). Previous growth chamber studies have found that canola was quite sensitive to seed-row MAP fertilization, with a significant negative impact occurring at rates of 30-40 kg P_2O_5 ha^{-1} and above (Qian & Schoenau, 2010). In the current study, there was a trend to reduced emergence after 5 days with increasing rate of seed-placed MAP and struvite, going from about 95 percent emergence at the 0 kg P_2O_5 ha^{-1} rate to 85 percent emergence at the 60 kg P_2O_5 ha^{-1} rate, but the effects were not significant at $\alpha = 0.05$ level of significance. Furthermore, emergence rates were similar between MAP and struvite. Also, reflecting the ability of canola to compensate for reduced emergence, no negative impact was observed on canola 30 day above ground biomass yield and P uptake with high P fertilization rate; with the canola P uptake maximized at 40 and 60 kg P_2O_5 ha^{-1}, which might be considered as luxury P uptake. Modern hybrid canola cultivars have not only greater yield potential than conventional cultivars but also greater vigor that may enable them to tolerate high rates of fertilizer P with the seed better, and to be able to better compensate for any stand reduction. However, one must be careful in extrapolating the results from trays in a growth chamber with controlled environmental conditions to a field condition.

Interestingly, the following wheat crop was very responsive to the P fertilizer that was added to the previous canola crop, with a more pronounced rate effect observed than for canola. The presence of residual fertilizer P in soil after canola growth significantly increased the wheat above ground biomass yield in comparison to the control, and the soil with 60 kg P_2O_5 ha^{-1} added to the previous canola produced the greatest wheat 30-day biomass yield. Overall, the following wheat crop appeared to benefit significantly from the fertilizer P applied to canola that was in excess of the canola P requirement and uptake potential.

The lack of response of the pea crop as the last crop in the rotation, to P fertilizer treatment added to canola, might be due to the depletion or fixation of soil residual P. However, significantly higher extractable available P levels remaining in the soil after the pea crop in the higher P rate fertilizer treatments suggest that the previous crops did not use all the fertilizer P applied, and that differences in P availability were present at the start of pea growth among the treatments that might have been expected to produce differences in pea yield and P uptake. Yield response of pulse crop to P fertilization is normally not large even under P deficient soil conditions (Gervais, 2009). Furthermore, as a pulse crop, pea is a good scavenger of P from the soil, and the differences in residual soil P level may not influence the pea crop significantly. Peas can develop strong mycorrhizal relationships when soil P levels are low and also acidify the rhizosphere to solubilize P minerals (Xie et al., 2017).

These findings support the concept of making larger P fertilizer applications to a crop than required to maximize yield, with the intention of having the unutilized fertilizer P carry over and provide benefit to subsequent crops. It has long been known that on low P soil, the buildup of background soil P levels combined with low rates of starter P fertilizer application can provide crops with very good growth benefits (Alessi & Power, 1980). However, the effect and degree of observed benefit from residual fertilizer P will depend on the following crop type. In the controlled environment study of this thesis, wheat greatly benefitted from increased residual soil P level, while pea did not show much response.

3.6.2 Effect of opener spread

In comparison to the 3” opener spread, the 1” opener spread resulted in a better biomass yield, P uptake, and P recovery in both canola and wheat. The soils from the Northern Great Plains are generally high in pH with high levels of calcium. The soil used in the pot study had a pH of 7.7, and in similar soils, phosphorus was shown to react strongly with calcium present in the soil and form sparingly soluble calcium compounds like brushite (Peak et al., 2012). Over time, these compounds would become increasingly less available by conversion to insoluble forms like apatite (Kar et al., 2017). The narrow 1” opener spread, which distributes the fertilizer across a lower proportion of the seed bed soil than the wide 3” spread opener, would be expected to result in a higher concentration of P per unit of soil and therefore greater potential for saturation of soil adsorption sites in the application zone as the fertilizer dissolves, keeping more P in solution. A wider spread may also increase the time for root access, enhancing the formation of insoluble P minerals (greater fixation) and the removal of available P from solution by sorption, all of which reduce the solubility and availability of added P fertilizer, and the carry over benefits for the following crop.

While seed-row P fertilizer application is an effective method that provides crop with early-season access to the fertilizer, plants may experience the fertilizer toxicity and root growth inhibition if the application rate is too high, especially when applied with seed in a narrow band (Bailey & Grant, 1990). The damage from high rate P fertilizer is related to salt damage (dissolution of the fertilizer salt) and ammonia (N) toxicity. The MAP (52-11-0) used in the pot study contains 11% N by weight (14 kg N ha^{-1} when MAP @60 kg P_2O_5 ha^{-1}). Canola is sensitive to N which can damage the seedling and negatively influence the crop (Grant et al., 2011; Malhi & Gill, 2004). The negative effect of a highly concentrated fertilizer band on early root growth is likely to be less in the ideal environment of a growth chamber compared to the field. The pots in the growth chamber were watered every two days, which would dilute or maintain the fertilizer concentration in the root zone at a safer level in comparison to where moisture is limited. Under controlled environment conditions, 1” opener spread resulted in a higher above-ground biomass yield and P uptake compared to wider opener spread. No fertilizer toxicity symptoms were observed in the controlled environment study of this thesis, suggesting that modern canola varieties may have a greater tolerance level under high P fertilization rates. As well as the sufficient moisture under the controlled environment condition dilutes the P concentration and reduces the P fertilizer toxicity.

Before the seeding of wheat, the crop root residues from the previous canola crop were removed to enable seeding, and the seed row was disturbed by the seeding of the wheat into the seed-row of the previous canola crop. However, wheat as the second crop in the rotation still showed response to the different opener spread. This also provides support for the concept that seed-row placed P fertilizer in the 1” band had less fixation and sorption, which provided the following crop with greater level of plant available P.

3.6.3 Influence of fertilizer MAP vs Struvite

There was no significant difference between MAP and struvite applied in the seed-row of canola on the 30-day biomass yield, P uptake and recovery of fertilizer P by the canola crop. Canola was responsive to P fertilizer application in both MAP and struvite form as it has high P demand and apparent ability to use P fertilizer effectively. It has been well documented that canola will positively respond to P fertilization with MAP, especially when soil P test values are less than 10 ppm. Canola has a combination of tap and fibrous root system that can explore significant soil volume and uptake P from the soil solution. Canola can proliferate its roots in areas with high P concentration, which enhances the ability of utilizing P fertilizer (Strong & Soper, 1974). When the concentration of fertilizer salts in the band is low, like many other crops, canola can acidify its rhizosphere by the exudation of organic acid which increases P availability (Hoffland, 1992; Hoffland et al., 1989). One study found that canola roots could lower the pH by 0.8 units (McKenzie et al., 1995). Unlike MAP, which is highly soluble in water, struvite is less soluble, but its solubility can be increased under acidic conditions (Ackerman et al., 2013). The organic acid released by root system of canola may give canola the ability to utilize applied P effectively in the form of struvite. Grant and Flaten (2019) suggested that a low solubility P fertilizer like struvite may show improved performance when soil - fertilizer contact is increased, such as by broadcasting or using a wider opener spread. However, there was no significant fertilizer form by opener spread interaction observed in the current study for any of the crops. The results of this thesis work demonstrate that struvite can be as effective as MAP for canola fertilization, at least under controlled environment conditions with suitable moisture and temperature, in agreement with results of Ackerman et al (2013).

Wheat in this study, as a following crop relying on residual fertilizer P left behind after the canola crop, had a slightly higher biomass response to struvite than MAP, but slightly lower P uptake with struvite compared to MAP. Similar to canola, wheat can develop roots that proliferate in soil areas with higher concentrations of available P, which is beneficial in accessing P from fertilizer (Strong & Soper, 1974), provided the concentration is not so high as to cause root avoidance. Slightly greater biomass response but slightly reduced P uptake response of wheat to residual P from struvite compared to MAP may be related to the less soluble nature of the struvite mineral and its reaction products. Addition of Mg in struvite might be expected to slow the conversion to less soluble apatite forms over time as noted by Kar et al (2017). However, the time elapsed in this growth chamber experiment from beginning to end (3 months) was much less than that which would occur in the field (3 years) using the same rotation. A detailed evaluation of the P reaction product species formed when MAP and struvite granules undergo dissolution, and their changes over time in the soil as the products age would be beneficial in helping to explain differences in plant yield response and P uptake.

Pea showed very little response to P fertilizer application form, rate and opener spread. As a pulse crop, pea has the ability to form mycorrhizal associations to assist in accessing soil P (Bailey and Grant, 1990), which makes pea a good scavenger for soil P. Therefore, as the third crop in the rotation, pea did not show much response to P fertilizer treatment and soil residual P from either P source.

When considering total P recovery, calculated by summing the P uptake attributable to fertilization for all three crops in relation to the P fertilizer applied at the beginning in the seed row of canola, the struvite had slightly lower apparent % recovery of the fertilizer P compared to MAP. This may be due to reduced availability to the plant of the fertilizer reaction products.

Overall, the findings of the growth chamber study indicate that struvite is a good alternative P source for canola that can also benefit following crops in rotation.

3.6.4 Residual soil P

Modified Kelowna and Ion Exchange Resin Membrane techniques showed a similar pattern in residual soil available P at the end of the three crops rotation (canola - wheat - pea) . As expected, fertilization rate had strong effect on residual soil P, where higher application rate left more fertilizer P in the soil behind as unused P, some of which is present in the labile, plant available P fraction extracted by chemical solution and ion exchange techniques. A noteworthy finding is that for the same high rate of P application of 60 kg P_2O_5 ha^{-1}, the MAP resulted in significantly greater residual available P according to soil assessment than struvite, which might be due to the lower solubility of struvite and its reaction products upon dissolution. However, the ability of successive crops to access residual struvite P similar to MAP P in terms of crop P uptake and recovery may also reflect the inability of the soil P residual analysis methods to account for plant rhizosphere and P solubilization effects.

The ATR-FTIR spectrum was not able to reveal differences in P forms present in the soil among different P fertilizer treatments. Even on the soil sample with 500 ppm P added, the concentration was still too low to allow sensitive detection of different P species abundance. A phosphorus k-edge XANES spectroscopy may be considered to further investigate the P mineral speciation as affected by different fertilizer sources.

4.0 Influence of Opener Spread, Row Spacing, and Rate of Phosphorus Fertilizer on Canola Biomass, Uptake and Recovery of Added Phosphorus

4.1 Preface

In chapter 4, field studies conducted in 2019 at five sites are reported. The field study examined canola response to different application rates of monoammonium phosphate fertilizer applied in the seed-row using different opener widths and row spacing configurations. In contrast to the controlled environment experiment covered in Chapter 3 which covered a three-crop rotation, the field study enabled examination of response of one crop, canola, to fertilization under field conditions at sites with contrasting soil and environmental conditions, reflecting actual conditions that producers would experience. Due to experimental site size limitations, only one fertilizer form, MAP, was evaluated in the field. Five locations across Alberta and Saskatchewan were included to provide contrasting soil and environmental conditions that can contribute to a refined recommendation for canola seed-row placed P fertilizer.

4.2 Abstract

Seed-row placement of monoammonium phosphate fertilizer is a common practice for P fertilization of canola crops on the Canadian prairies, as MAP provides canola with "starter" benefits in early P nutrition. The existing recommendation for seed-row placed P fertilizer was developed using only one opener spread and row spacing configuration, with no field evaluations of impact on biomass yield, P uptake and recovery. Field studies were conducted in 2019 at five sites across the western prairies: western Alberta (Lethbridge), eastern Alberta (Brooks), western Saskatchewan (Scott), central Saskatchewan (Saskatoon) and eastern Saskatchewan (Melfort) to evaluate canola response to MAP application under different seed bed utilization (SBU) achieved using different opener widths and row spacing combinations. The MAP application rates were 0, 22, 39, 56, and 73 kg P_2O_5/ha with 1", 2", and 4" opener spread and 9" and 12" row spacing, all of which generates a SBU ranging from 8% to 44% of the seed bed used for placing the seed and fertilizer together in the same furrow. Canola had significant positive biomass yield (above ground plant material at maturity) responses to P fertilization at most sites, where higher rates of seed-row placed MAP promoted a greater canola biomass yield, with the greatest incremental yield increase associated with the first incremental P addition of 22 kg P_2O_5 ha^{-1}, which then leveled off at higher rates. Across the sites, the canola biomass yield and P uptake were generally maximized at rates of 39 to 56 kg P_2O_5 ha^{-1}. No significant negative response was observed on the canola crop biomass at maturity up to the highest 73 kg P_2O_5 ha^{-1} rate. At three of the five sites (Brooks, Scott and Lethbridge), significantly higher canola biomass yield and P uptake were observed with the highest SBU (44%), with limited and non-significant effects of SBU at Saskatoon and Melfort sites. This may reflect a benefit from higher SBU in the field promoting earlier root extension and greater exploration of the soil volume.

4.3 Introduction

To maximize canola yield, prairie producers typically apply phosphorus (P) fertilizer to supply sufficient P for the current crop and also replace the phosphate removed from the system due to crop removal and environmental factors such as erosion of particulate P and transport of soluble P in water (Wiens et al., 2019). Annual crops should be supplied with sufficient phosphorus at very early stages as P is needed for energy production, cell division, and growth in the early developmental stages (Grant and Flaten, 2019). Therefore, placement of P fertilizer in a location in the soil so that the roots of the germinating seedling can access is very important, especially in northern prairie soils that are still cold after planting and root growth is restricted.

Phosphorus is not very mobile in soil, and cold soil temperatures can further reduce the solubility and movement of soil P by diffusion, making P even less available to the crop. However, P fertilizer can be toxic if concentration near the seed is too high. A high rate of seed row P fertilizer placement such as that exceeding 30 kg P_2O_5 ha^{-1} could cause potential salt injury to young seedlings of many crops including canola (Qian et al., 2012). Canola is particularly sensitive to P fertilizer. The recommended seed-placed P fertilizer safe rates are 15 lb P_2O_5 ac^{-1} in Alberta, 20 in Manitoba, and 25 in Saskatchewan, although those rates do not replace all the P that is removed in the grain of a high yielding canola crop. The current maximum safe rate of seed-placed P for Saskatchewan is based on 1" opener and 9" row spacing (~15 percent seed bed utilization), and there is little or no information on the relationship between opener width, row spacing and its influence on performance in terms of yield, plant P uptake and recovery. Furthermore, the Canola Council of Canada (CCC, 2017) suggests that "as seedbed utilization increases, growers can proportionally increase seed-placed P fertilizer rate." Seed-bed utilization is the opener spread width divided by the row spacing width and is the proportion of the seed-bed area utilized for placement of the seed and fertilizer together. The greater the seed bed utilization, the greater the average distance between fertilizer granule and seed, and the less potential for injury from the salt effect. However, the relationship between % seed bed utilization and P availability is not well documented. Research conducted under controlled environment conditions and reported on in Chapter 3 of this thesis suggested that under controlled environment conditions and confined rooting (growing plants in trays), a lower seed bed utilization where fertilizer is more concentrated in the furrow, accomplished by a narrower opener spread, increased P availability and uptake for canola. However, opener spread, and row spacing effects require evaluation under field conditions.

While emergence and yield effects of different rates of seed-row placed fertilizer under a single opener and row spacing configuration have been evaluated in previous studies (Qian et al., 2012), no studies have evaluated how opener spread and row spacing might affect the recovery and efficiency of utilization of the applied P fertilizer by the crop. The spread and distribution of P fertilizer across the seed-row can potentially influence the degree of contact and fixation of the added fertilizer with soil constituents, and the ability of roots of the crop to access the P early on. The research in this chapter addresses this gap in knowledge by determining the effect of opener spread and row spacing on MAP fertilizer utilization under field conditions using five field site locations extending from southern Alberta to east-central Saskatchewan.

4.4 Materials and methods

4.4.1 Site description

Field experiments were established at five locations including Lethbridge (western Alberta), Brooks (eastern Alberta), Scott (western Saskatchewan), Saskatoon (central Saskatchewan) and Melfort (eastern Saskatchewan). The trials were located on Agriculture and Agri-Food Canada Research farms on well-drained soil without salinity and flooding issues. Experimental lands were selected in areas of the AAFC research stations where wheat had been grown.

4.4.2 Field study experimental design

The field study described in this thesis is part of a larger study by Agriculture and Agri-Food Canada conducted in 2018 and 2019. The treatments employed in the 2019 field study locations utilized in this thesis research were: 1) row spacing at 9" and 12"; 2) opener spread at 1", 2", and 4"; 3) P rate at 0, 20, 35, 50, and 65 lb P_2O_5 ac^{-1} (0, 22, 39, 56, and 73 kg P_2O_5 ha^{-1}) added as monoammonium phosphate fertilizer (MAP 11-52-0). At each site, each replicate plot was 15 m in length and 1.7 m wide with a 0.5 m pathway surrounding the plot. The treatments were arranged in a randomized complete block design (RCBD) with four blocks of replicate treatments. The canola was established on cereal stubble. The treatments outlined above involved 2 row spacings x 3 opener widths to give six seed bed utilizations x 5 P rates x 4 replications of each treatment x 5 locations = 600 plots. As an example, the plot diagram depiction for the Saskatoon site is included in the appendix (Table A-3). Environmental conditions (monthly cumulative precipitation, and mean air temperatures) for the 2019 growing season months of May, June, July and August were obtained from Environment Canada meteorological stations near the sites and are provided in Table 4.1

4.4.3 Canola seeding and fertilizer treatment application

Canola seed (cv. Liberty Link L233P) with a thousand Kernel seed weight (TKW) of 4.5g was seeded at 6 lb/ac (6.72 kg ha^{-1}) at all the locations in May of 2019. The seed was pre-treated with Lumiderm ™ and Prosper Evergol ™ which contains the insecticide cyantraniliprole and fungicides penifluten, trifloxystrobin, metalaxil along with an insecticide clothlanidin, respectively. Weed control was accomplished by use of glufosinate prior to bolting of the canola crop. The seeding and fertilization treatment applications were accomplished at each site by using a custom-made plot drill fitted with Morris Contour 1 shanks, rollers, and Dutch Universal openers with the ability to easily change the opener type and width, as well as row spacing. At each site, 157 kg N ha^{-1} urea (46-0-0) and 22 kg S ha^{-1} ammonium sulphate (21-0-0-24) was banded in all plots to a depth of three inches at seeding through disk openers mounted on the front part of the seeder. Phosphorus fertilizer treatments were seed-row placed through the different openers mounted on the Morris Contour 1 shanks. Other agronomic managements including insect and disease control through pesticide applications were done by local research site staff at all five locations as required. To protect the soil in the alleyways, fall rye or winter wheat was planted around the plot area and pathways and mowed regularly.

4.4.4 Soil analysis

Soil samples were taken in spring of 2019 from each plot before seeding at the depths of 0-15, 15-30, and 30-60 cm to determine background soil characteristics. Four cores were taken from each replicate plot and soil analysis was conducted for available P, NO_3-N, NH_4-N, K, S, Fe, Zn, B, Mn, SOM, pH, EC, and soil texture (particle size) determination (Table A-4). The summarized baseline soil data is shown in Table 4.2. The analytical methods used for assessment of soil available P using the modified Kelowna method (Qian et al., 1994) are described in detail in Chapter 3 of this thesis.

4.4.5 Plant analysis

This thesis project measured the canola crop total aboveground biomass yield taken at crop maturity just prior to the start of senescence. This time of crop sampling was used as it provides the best measurement of total above-ground plant uptake of P that includes the entire growth period, before any leaf drop and loss of P containing plant material occurred. This was necessary to accurately measure total above-ground P content and uptake by the canola. Canola aboveground biomass was cut from two ends of each plot using a square meter at each location. In addition, four representative intact plants on the edge of these 2 square meters were carefully collected and bagged separately for P concentration analysis. The plants were placed in a cotton bag and retained in a drier at 60 ^{o}C until completely dry. The dried plant samples were coarsely ground using a Wiley™ mill followed by the Udy™ mill for fine grinding in preparation for a sulphuric acid peroxide digestion (Thomas et al., 1967) followed by automated colorimetry, which has been described in detail previously in Chapter 3 of this thesis.

4.4.6 Key calculations and statistical analysis

The equations used to calculate canola P uptake in above ground biomass and fertilizer P recovery in the above-ground portion of the mature canola crop are provided below. Note that the control is the comparable placement and fertilizer type treatment without P fertilizer added.

P uptake = crop P concentration x crop above-ground biomass

Canola fertilizer P recovery = $\frac{treatment\ P\ uptake - control\ P\ uptake}{P\ application\ rate}$

The statistical analyses were conducted using RStudio (ver. 1.2.1335) software. A multi-factor ANOVA was conducted with the means separated by Tukey-HSD test. Outliers were detected using Grubbs test and removed. Specific information on which samples were removed can be found in the appendix (Table A-2).

4.5 Results

4.5.1 Weather data

Table 4.1: Average monthly air temperature and precipitation in 2019 and the previous 5-year (2015-2019) average using data from the nearest Environment Canada weather station.

		2019		Average 2015 - 2019	
Site	Month	Air Temperature ºC	Precipitation (mm)	Air Temperature ºC	Precipitation (mm)
Saskatoon	May	9.7	4.4	12.5	30.8
	June	16.0	84.8	17.0	28.5
	July	17.8	67.6	19.1	49.9
	August	15.4	20.3	17.3	39.5
	September	12.3	39.5	11.0	35.1
	Total		216.6		183.8
Brooks	May	10.1	7.2	12.5	29.1
	June	16.1	26.4	16.8	48.0
	July	18.2	46.6	19.2	41.5
	August	17.3	26.0	17.8	25.5
	September	12.1	42.0	11.5	24.8
	Total		148.2		168.9
Lethbridge	May	10.3	58.7	11.8	40.8
	June	15.1	47.0	16.3	25.1
	July	17.6	31.3	18.8	23.2
	August	17.7	24.5	18.1	19.6
	September	12.7	32.8	12.5	19.5
	Total		194.3		128.1
Melfort	May	8.8	18.8	12.1	27.2
	June	15.3	87.4	16.4	49.7
	July	16.9	72.7	18.1	95.3
	August	14.9	30.7	16.6	46.1
	September	11.2	43.0	10.8	41.6
	Total		252.6		260.0
Scott	May	9.1	12.7	11.7	41.9
	June	14.9	97.7	15.8	26.0
	July	16.1	107.8	17.9	51.3
	August	14.4	18.0	16.4	62.3
	September	11.3	41.8	10.0	35.7
	Total		278		217.1

†Saskatoon and Brooks had supplemental irrigation at beginning of May to enable germination.

Environmental conditions (monthly air temperatures and precipitation) at the five sites in 2019 along with the previous five years (2015-2019) are shown in Table 4.1. May was drier than June at all sites, and due to extremely dry conditions at Saskatoon and Brooks in May, these sites received approximately 10 mm of supplemental irrigation to enable canola seed germination. Overall, the total growing season precipitation (May-September) in 2019 followed the pattern: Scott > Melfort > Saskatoon > Lethbridge > Brooks. Saskatoon received below average rainfall in the spring, with supplemental irrigation provided in May and above average rainfall through the early summer toward the end of the growing season including a wet June with almost three times more rainfall than the 2015-2019 average. The Brooks site, which like Saskatoon site also received supplemental irrigation in spring, had below average rainfall in the spring and early summer and similar total precipitation in comparison to the 5 years average, with drier conditions in the early season. Lethbridge had more rainfall throughout the growing season in comparison to the 5-year average and was the second driest site for total growing season precipitation in 2019. Melfort had a dry May but received a significant amount of rainfall since early summer, where June had almost double the previous 5 years average rainfall. Scott had a drier May and August, but June and July had more than double the rainfall compared to the past 5 years. Overall, Scott received the most rainfall and Brooks received the least.

4.5.2 Soil properties

Table 4.2: Basic soil characteristics at the five sites in spring of 2019 as determined by soil cores taken from the 0-15 cm depth (n=16) across the plot areas prior to seeding. Values presented are means (n=16) followed by the standard deviation of the mean in brackets.

	Saskatoon	Brooks	Lethbridge	Melfort	Scott
OM (%)	4 (0.12)	1.9 (0.10)	4.3 (0.42)	8.3 (0.67)	4.4 (0.20)
pH	8 (0.11)	7.8 (0.21)	7.9 (0.13)	7.1 (0.27)	6.8 (0.25)
EC (ds/m)	0.4 (0.04)	0.2 (0.02)	0.4 (0.02)	0.2 (0.02)	0.2 (0.02)
Clay (%)	43.4 (0.74)	19.6 (0.87)	48.7 (0.68)	46 (2.80)	17.8 (0.42)
Sand (%)	20.8 (1.20)	40.3 (0.87)	19.2 (0.57)	17.7 (0.72)	37.8 (2.15)
Texture	Silty Clay	Silt Loam	Silty Clay	Silty Clay	Silt Loam

† Soil texture was determined using Soil Texture Triangle (Watson, 2016).

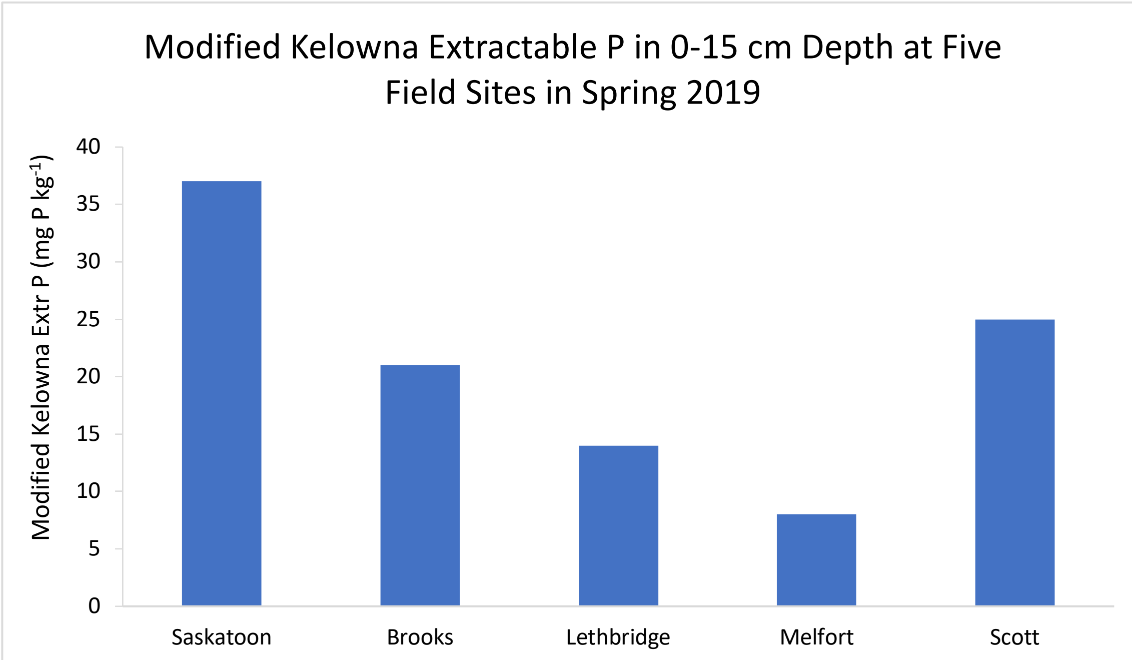

Figure 4.1: Mean (n=16) Modified Kelowna extractable P (mg P kg^{-1}) from soil analysis of 16 soil cores (0-15cm) collected from across the plot area of each site, where Saskatoon: 37 mg P kg^{-1}, Melfort: 8 mg P kg^{-1}; Lethbridge: 14 mg P kg^{-1}; Scott: 25 mg P kg^{-1}; and Brooks: 21 mg P kg^{-1}. Degree of soil P deficiency: very low to medium: less than 15; Medium to High: 15-30 ; High to Excessive: above 30 (Grant and Flaten, 2019).

The Saskatoon site had the greatest soil extractable P level among all five locations, considered high to very high in available P according to Grant and Flaten (2019). The Melfort and Lethbridge sites are rated as low to medium in availability of P while Scott and Brooks site had medium to high levels of extractable soil P where Scott had averaged 25 ppm extractable soil P which is greater than Brooks location. Overall, according to soil test, the relative availability of P at the five sites is Saskatoon > Scott > Brooks > Lethbridge > Melfort.

4.5.3 Canola yield, P uptake and recovery responses at the different site locations

The greatest above ground biomass (grain + straw) yield of canola was found at the Saskatoon site with the lowest yields at the Lethbridge site (Table 4.3). This is consistent with high fertility and use of supplemental irrigation in the spring at the Saskatoon site and dry conditions in the 2019 growing season at Lethbridge site. Phosphorus uptake in above ground biomass followed a similar pattern to yield and amounts of P uptake were similar to those reported in other studies, ranging from ~ 5 to 23 kg P ha^{-1} at the sites (Table 4.3) The apparent recovery of added fertilizer P in the above ground biomass material, averaged across treatments, ranged from ~ 6% at Lethbridge to ~ 16% at Melfort. Low fertilizer P recovery at Lethbridge is consistent with low yields and uptake potential that was hampered by dry conditions.

Table 4.3 Effect of site location on canola crop biomass yield, P uptake, and % recovery of added P fertilizer in above-ground biomass in the 2019 field study. For a parameter, means followed by the same letter are not significantly different based on Tukey`s HSD test at α=0.05 level of significance.

	Location				
Parameter	Saskatoon	Brooks	Lethbridge	Melfort	Scott
Biomass yield (kg ha^{-1})	10625 a	8000 c	4165 d	7860 c	9136 b
P uptake (kg P ha^{-1})	21.5 a	15.4 b	5.1 c	14.5 b	22.7 a
% P recovery	11.6% ab	12.4% ab	6.2% b	16.3% a	12.1% ab

4.5.4 Canola yield, P uptake and recovery response to treatments

Across the sites, phosphorus fertilizer application rate was a major treatment variable affecting the canola crop above ground biomass yield and P uptake (Table 4.4). Row spacing had a significant effect on canola crop parameters at four of the five experimental sites, especially at Lethbridge, where biomass yield, P uptake, and % P recovery had highly significant ($p<0.01$) responses to row spacing. Opener spread significantly affected the biomass yield at Lethbridge and Scott, and P uptake at Brooks and Scott. There was significant effect of row spacing and opener spread interaction on biomass yield and P uptake at Brooks site and on P recovery at Melfort, and a significant row spacing and rate interaction on biomass yield at Scott site.

Table 4.4: ANOVA summary table of canola crop parameters collected from five sites across Alberta and Saskatchewan in 2019. Reported values are p values.

		Effect						
Location	Parameter	Row Spacing	Opener Spread	Rate	Row*Opener	Row*Rate	Opener*Rate	Row*Opener*Rate
Saskatoon	Biomass yield	**0.0001** ***	0.5584	0.1358	0.5159	0.7953	0.7366	0.5319
	Uptake	0.0695	0.2134	0.1334	0.3046	0.7889	0.8469	0.8147
	Recovery	0.1690	0.5530	0.3980	0.3200	0.9310	0.9260	0.7180
Brooks	Biomass yield	**0.0346** *	0.2358	**0.0088** ***	**0.0003** *	0.8823	0.2700	0.3814
	Uptake	0.6889	**0.0538** *	**0.0037** ***	**0.0037** *	0.8907	0.7556	0.9347
	Recovery	0.4720	0.3780	0.8150	0.1880	0.8950	0.9010	0.8640
Lethbridge	Biomass yield	**0.0001** ***	**0.0032** ***	0.1538	0.0822	0.9890	0.8202	0.8055
	Uptake	**0.0002** ***	0.2021	**0.0013** ***	0.1354	0.9778	0.8808	0.4945
	Recovery	**0.0035** ***	0.1701	0.5902	0.6170	0.8297	0.6029	0.1711
Melfort	Biomass yield	0.6560	0.6980	**0.0001** ***	0.2770	0.4470	0.7610	0.4570
	Uptake	0.7840	0.8070	**0.0001** ***	0.1410	0.8170	0.8200	0.4070
	Recovery	0.9192	0.6463	0.8440	**0.0394** *	0.5436	0.6729	0.5456
Scott	Biomass yield	0.0685	**0.0044** ***	**0.0104** **	0.0634	**0.0243** *	0.1352	0.3740
	Uptake	0.1744	0.0910	**0.0005** ***	0.0715	0.3545	0.5847	0.4969
	Recovery	0.9350	0.1340	0.3360	0.1870	0.6550	0.2480	0.5420
Combined	Biomass yield	0.9824	0.3209	**0.0047** ***	0.1540	0.8481	0.9895	0.8870
	Uptake	0.9129	0.2384	**0.0013** ***	0.5791	0.8286	0.9970	0.9382
	Recovery	0.5610	0.1600	0.3230	0.1460	0.6730	0.8990	0.4390

†Bolded number followed by *** indicates *p-value* < 0.01; ** indicates *p*-value between 0.01 and 0.05; and* indicates *p-value* greater than 0.05 and less than 0.10.

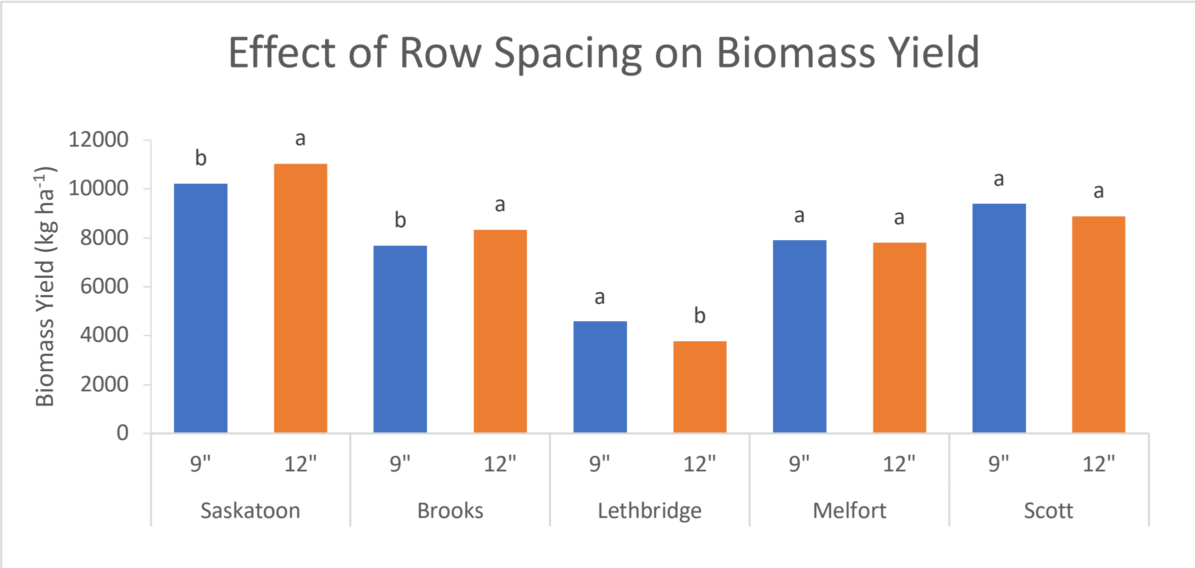

Figure 4.2: Canola crop above ground biomass yield response to row spacing at the five locations in 2019. Means were separated using Tukey's HSD test (α=0.05). At a site, bars followed by a different letter represent a significant difference.

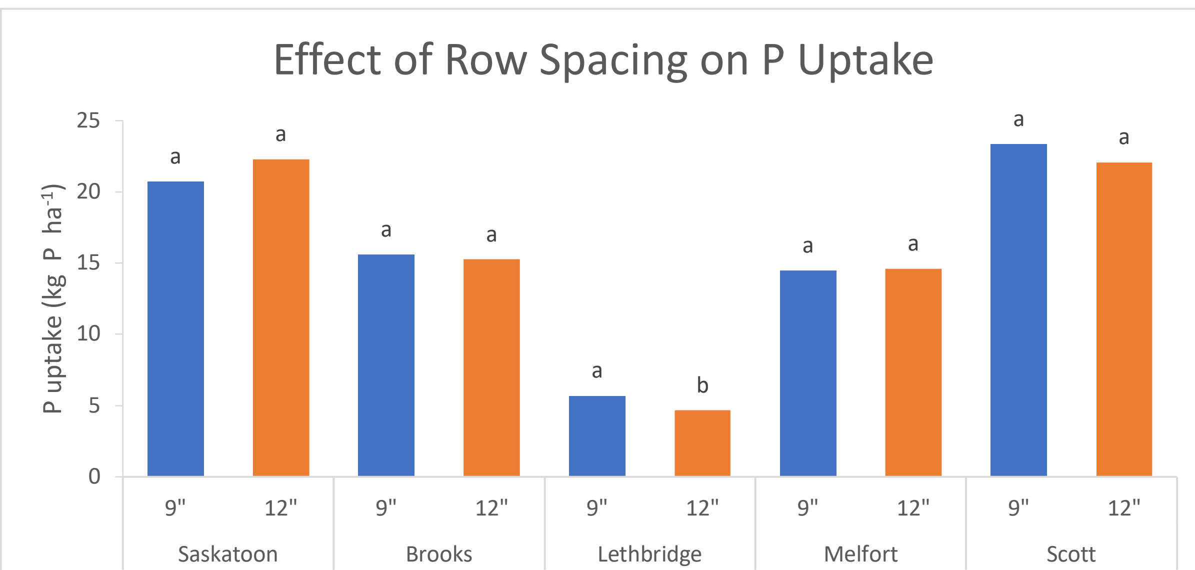

Figure 4.3: Canola crop P uptake in response to row spacing at the five locations in 2019. Means were separated using Tukey's HSD test (α=0.05). At a site, bars followed by a different letter represent a significant difference.

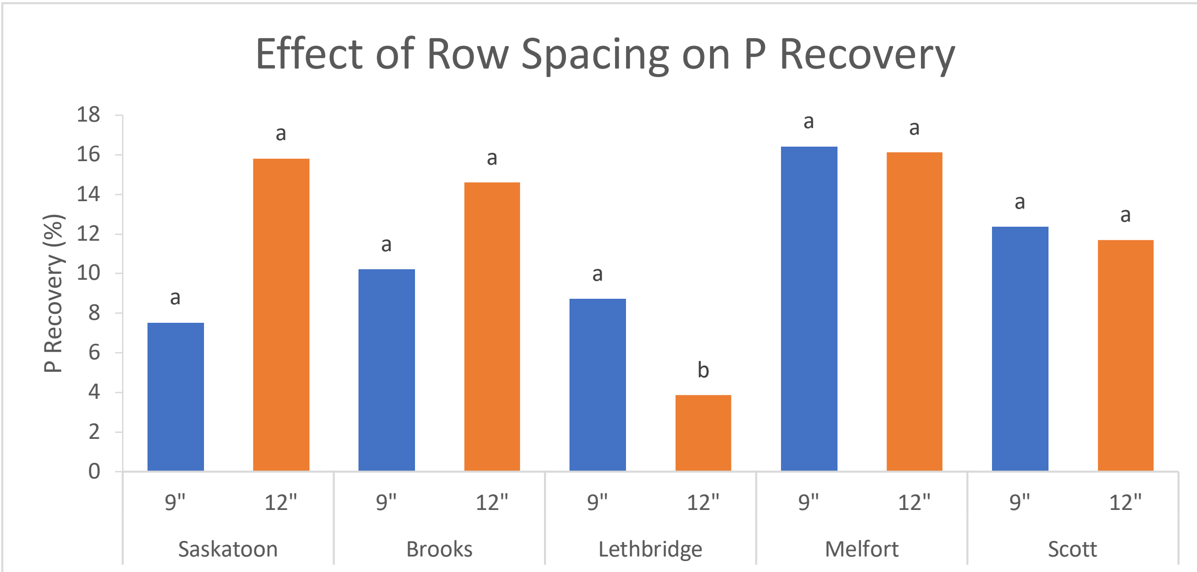

Figure 4.4: Recovery of fertilizer P (% of P fertilizer applied) in canola crop biomass in response to row spacing at the five locations in 2019. Means were separated using Tukey's HSD test (α=0.05). At a site, bars followed by a different letter represent a significant difference.

Lethbridge was the only site where row spacing had a significant effect on all three crop parameters tested: canola crop biomass yield, P uptake and % P recovery (Figures 4.2, 4.3 and 4.4). At Lethbridge, narrower row spacing (9”) resulted in higher biomass yield, P uptake and fertilizer P recovery in comparison to 12” row spacing. This may reflect a particular advantage in having the fertilizer more evenly distributed across a greater proportion of the seedbed under drier conditions in compare to other sites. At Saskatoon and Brooks, above-ground biomass yield data indicated that 12” row spacing had significantly higher biomass yield response than the narrower 9” spacing (Table 4.3, Figure 4.2). At Scott and Lethbridge, 4” opener spreads had significantly higher biomass yield compared to 1” spread (Figure 4.5).

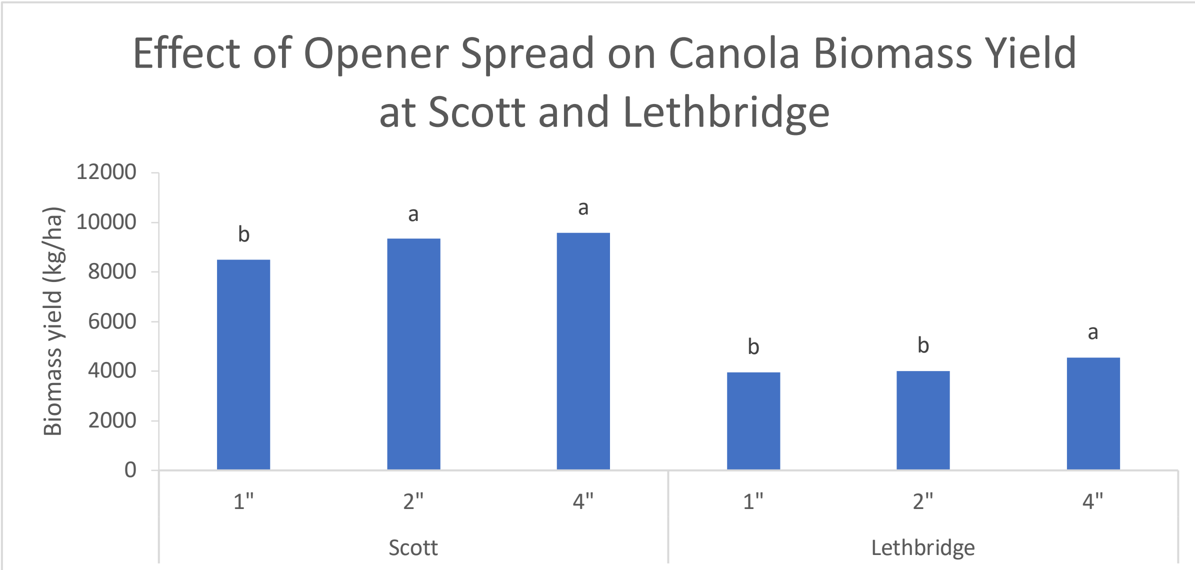

Figure 4.5: Canola crop biomass yield in response to opener spread width at Scott and Lethbridge sites in 2019. Means were separated using Tukey's HSD test (α=0.05). At a site, bars followed by a different letter represent a significant difference.

At locations with low to medium soil P availability (Melfort, Scott and Brooks), increasing P fertilizer rate increased canola crop biomass yield and P uptake (Figure 4.6). At Lethbridge, P uptake was also increased to a small degree by P fertilization, with dry conditions likely reducing the response despite soil P deficiency. The Saskatoon site did not respond to P fertilizer application rate in any of the three parameters, which can be explained by high levels of available soil P as revealed by soil P test results (Figure 4.1). Combined data indicated that P fertilization significantly increased the canola crop biomass yield at 56 and 73 kg P_2O_5 ha^{-1} and P uptake at 39, 56, and 73 kg P_2O_5 ha^{-1} over the unfertilized control. Furthermore, canola at Scott produced a small biomass yield and P uptake decrease at 73 kg P_2O_5 ha^{-1}; however, the difference was not significant (Figure 4.6). All of the canola crop parameters at the Lethbridge site were significantly lower in comparison to other experimental sites, which may be due to the dry conditions.

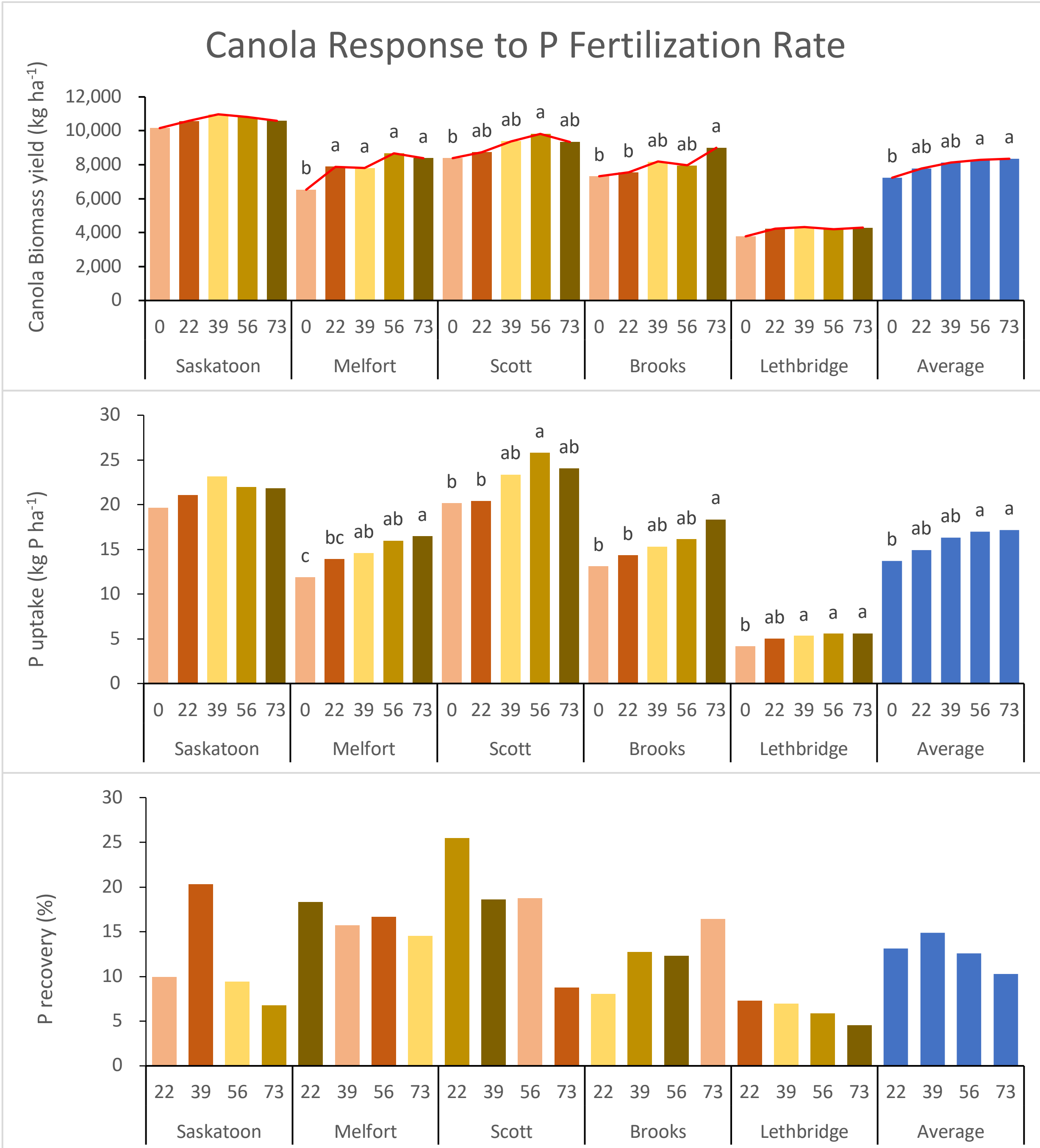

Figure 4.6: Effect of MAP (11-52-0) fertilization rate (kg P_2O_5 ha^{-1}) on canola crop biomass yield, P uptake, and % P recovery at the five field locations in 2019. At a site, bars followed by a different letter represent a significant difference based on Tukey`s HSD test at α=0.05. (Table-A6)

The canola crop had significant response to the interaction effect of row spacing and opener spread at the Melfort and Brooks sites (Figure 4.7). At Brooks site, the greatest biomass yield was observed with 2” opener and 12” row spacing, while the highest P uptake was observed with the 4” opener spread and 9” row spacing. The Melfort site was the only location that had significant P recovery response to the opener spread and row spacing, where the highest fertilizer P recovery was from 1” opener and 9” row spacing.

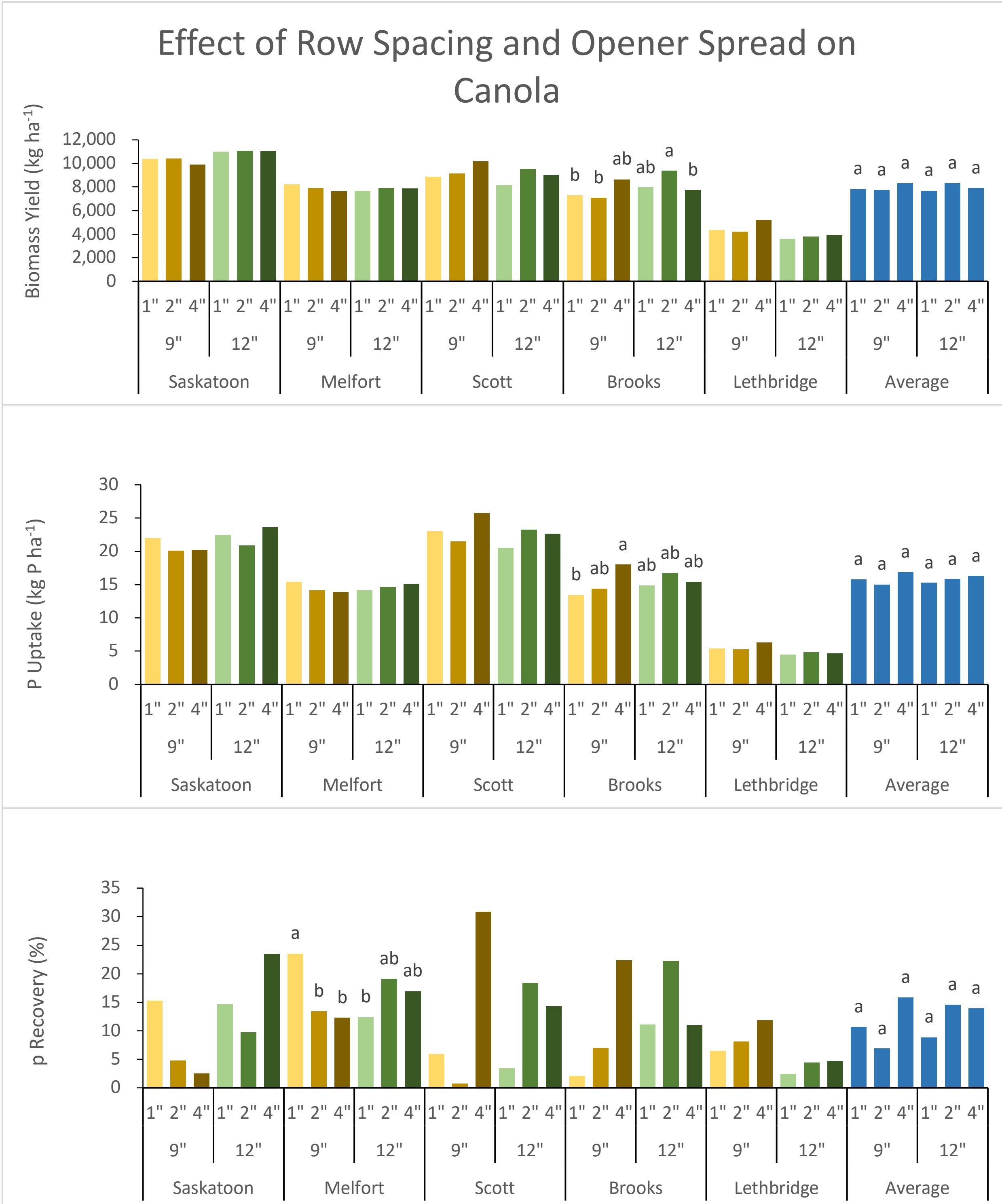

Figure 4.7: Effect of opener spread and its interaction with row spacing on canola crop biomass, P uptake and % of added P fertilizer recovered in biomass at the five locations in 2019At a site, bars followed by a different letter represent significant difference based on Tukey`s HSD test at α=0.05.

The combined influence of opener spread and row spacing may also be considered in terms of seed bed utilization (SBU). The SBU is calculated by dividing the opener spread by the row spacing and represents the proportion of the seed bed area that is used to place seed and fertilizer together (Roberts and Harapiak, 1997). A lower seed bed utilization value is associated with the seed and fertilizer granules on average being closer in distance to one another. This means that a high concentration of fertilizer in solution from granule dissolution ends up being in closer proximity to the seed and seedling roots with lower SBU. The 8%, 17%, and 33% SBU at Saskatoon resulted a greater yield compared to 44% SBU, while 17% SBU resulted in highest biomass yield at Brooks, and 17% and 44% SBU had greater biomass yield compared to 8% SBU at Scott (Figure 4.8). The largest SBU of 44%, achieved with the narrowest row spacing of 9" and greatest opener spread of 4", was associated with the highest biomass yield at Lethbridge. Furthermore, canola at Scott, Brooks and Lethbridge sites had highest P uptake and fertilizer P recovery at the highest (44%) SBU. Averaged across the sites, the highest mean P uptake and fertilizer P recoveries were achieved at the highest SBU of 44% (4" spread and 9" row spacing).

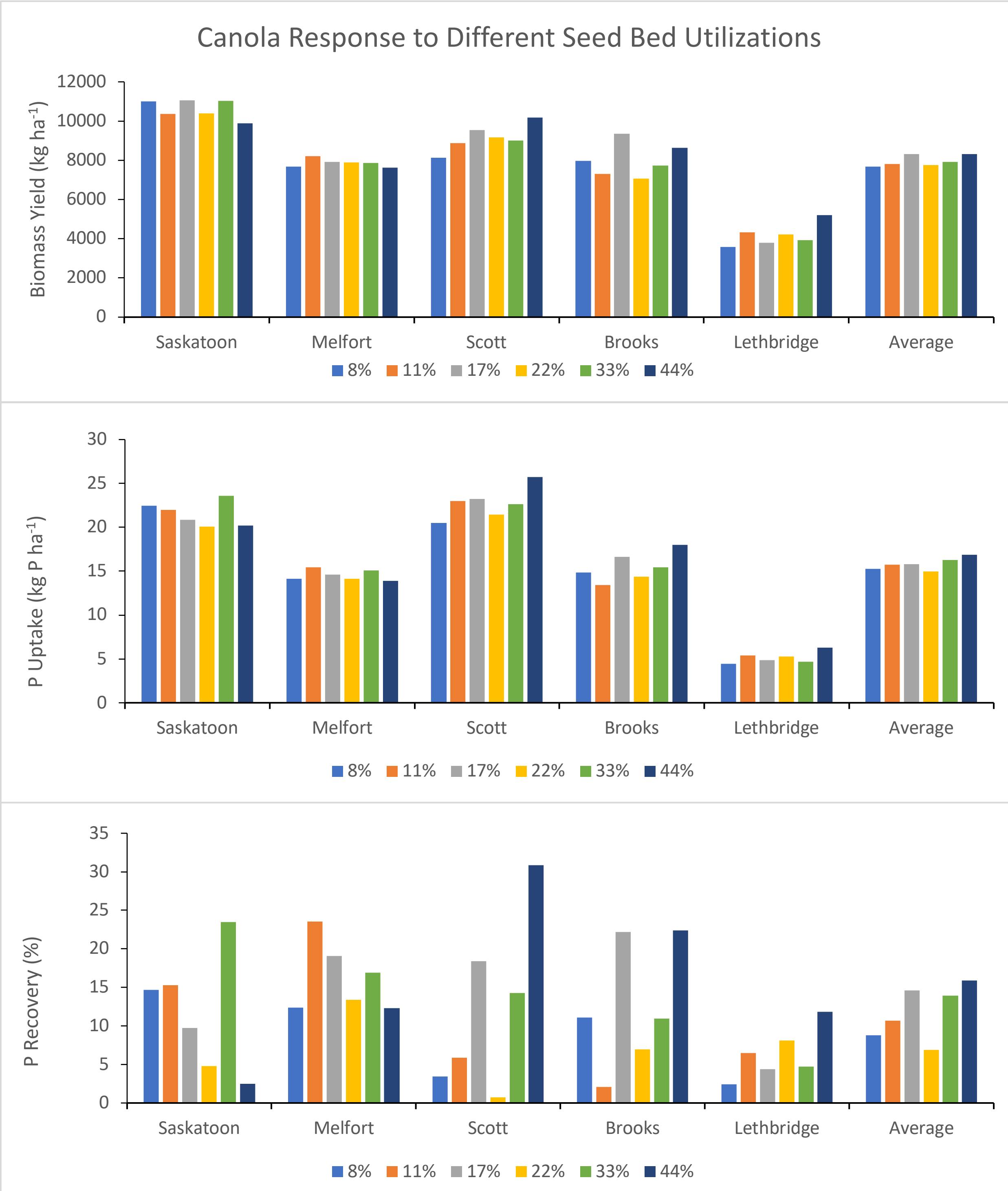

Figure 4.8: Response of canola biomass yield, P uptake and recovery of P fertilizer to the different seed bed utilization values (opener spread divided by row spacing) achieved in the different opener spread and row spacing treatments employed in the field study.

The Scott site was the only site where row spacing and its interaction with fertilization rate had a significant effect on canola crop biomass yield (Figure 4.9). The 9” row spacing with 39 and 56 kg P_2O_5 ha^{-1} application rate, and 12” row spacing with 56 kg P_2O_5 ha^{-1} application rate had significantly higher yield over control (0 kg P_2O_5 ha^{-1}) with 12” row spacing. A wide row spacing may aggravate deficiency due to root competition when plant populations are high within a row. This would be apparent with no fertilizer P applied or at low application rates.

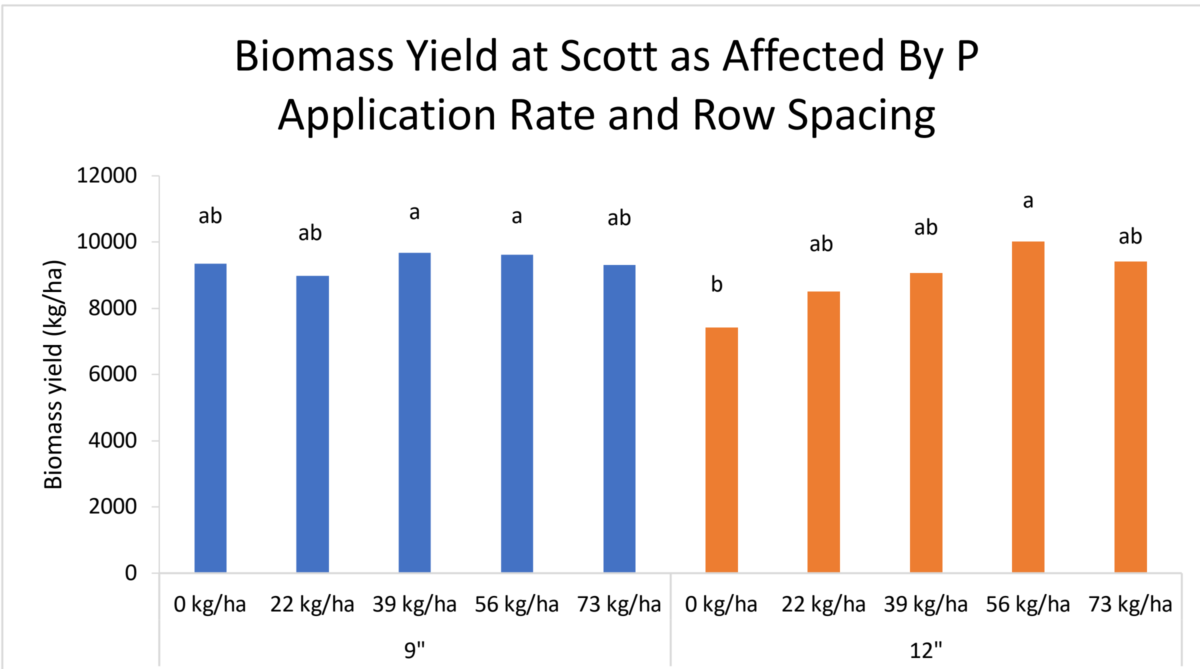

Figure 4.9: Canola crop biomass yield at Scott site in 2019 in response to application rate using two different row spacings. Means were separated using Tukey's HSD test (α=0.05). Bars with different letters are significantly different.

4.6 Discussion

Monoammonium phosphate (MAP, 11-52-0), which is the most common form of phosphorus fertilizer used across the Northern Great Plains, was selected as the P fertilizer form to provide available P to the canola crop in the field study. MAP is a water-soluble granular form of P fertilizer that provides plants with both ammonium and phosphate ions. Environmental conditions, and interactions between soil, fertilizer and roots may alter the solubility and availability of the added P once the granule of MAP dissolves in soil solution. A series of reactions are initiated when MAP fertilizer dissolves in the soil solution. The phosphate in the soil solution will eventually react with cations including calcium and magnesium present in the soil solution common in prairie soils, which forms increasingly less soluble precipitated compounds over time that reduces the P availability to the crop (Havlin et al., 2014).

In the field component of this thesis, canola was grown at five different locations across Alberta and Saskatchewan, which provides a contrast in soil and environmental conditions as they potentially affect canola growth, P fertilizer behavior and overall response to P fertilizer management. The response to application rate of MAP and the effect of row spacing and opener spread configurations used in seed placement of the MAP fertilizer was evaluated. Depending on local climate and soil conditions and residual nutrient levels, canola may behave differently, all of which can add insight and help refine P fertilizer recommendations for optimum rate, opener spread and row spacing to maximize plant yield, P uptake and fertilizer P recovery.

4.6.1 Canola response to P fertilizer rate

As expected, canola responded to P fertilization rate at most sites, with greater yield response observed with a higher P fertilizer application rate and greater response at sites with lower initial soil available P (Figure 4.1). Similar to the controlled environment study described in Chapter 3, the first few kg of P fertilizer added at the field study sites generally gave the greatest incremental increase in biomass yield, with a progressive levelling off at higher rates (Figure 4.6). The biomass yield and P uptake were generally maximized at 39 to 56 kg P_2O_5 ha^{-1}.

Canola grown at the Saskatoon site did not significantly respond to fertilization in biomass yield, P uptake, or percentage of fertilizer P that was applied and recovered in the above ground biomass. The higher level of residual available P at this site explains the lack of response (Figure 4.2). Using the “short-term sufficiency P application strategy”, where the P fertilization rate is dependent on the anticipated availability of existing soil P to the crop throughout the growing season (Grant and Flaten, 2019), the amount of fertilizer added should be adjusted accordingly to the P requirement that optimizes crop yield that season. However, if the soil P level is high enough to entirely supply the P needed for maximum crop growth, the addition of P fertilizer might be unnecessary to maximize yield that year, but P fertilizer would need to be added to replace the P removed in crop harvest in order to maintain soil P levels and fertility for following years crops. A field study conducted in central and north-central Alberta found that on soils with extractable P greater than 22 ppm, there was no economic benefit from P fertilizer application (Nyborg & Hennig, 1999). Studies in Manitoba illustrated that crops are unlikely to respond greatly to fertilizer P application when the Olsen extractable P levels are over 18 ppm (Table 4.5).

Table 4.5: Crops response to soil P concentration (Olsen soil test) in Manitoba (Hedlin, 1962).

Available P (ppm Olsen soil P test)	Number of Experiments	% Responding to P fertilizer
0-5 (Very Low)	15	100
5-12 (Low to Medium)	50	62
12-18 (Medium to High)	16	56
>18 (High to Very High)	14	29
Overall	95	63

It is important to note that the yield assessment in the current study is the total above-ground biomass and does not separate into seed and straw yield. Studies in Alberta that measured grain yield found 60% of canola sites responded to P fertilization on soil with above 30 ppm extractable P based on a two bushel yield increment (McKenzie et al., 1995). In the current study, the Saskatoon site had over 30 ppm of extractable P and did not respond to P fertilization in above-ground biomass yield. Similarly, canola biomass had no significant response to P fertilization rate at Lethbridge site likely due to other yield limiting factors. However, greater canola P uptake is attained when P fertilization increased further at the Lethbridge site (Figure 4.6). Unlike the Saskatoon site, Lethbridge has a low to medium level of MK extractable P but also received the least amount of moisture/rainfall during the growing season, which would reduce yield potential and crop demand and also might reduce the availability of applied P fertilizer. The Melfort site, which had the lowest soil MK extractable P, had the most significant response to P fertilization (Table 4.4, Figure 4.6). Both initial available P and growing season conditions affect yield potential and crop demand. Therefore, both are important factors affecting above-ground biomass yield response of canola to seed-placed fertilizer P. No evidence of crop damage was observed in the form of decreased biomass yields at the highest rates of seed placed P in this study (73 kg P_2O_5 ha^{-1}), indicating considerable tolerance and resistance of canola to seed row placement of fertilizer P.

Canola exhibits a decreasing response to P fertilizer application with increased soil available P concentration, as canola can effectively use soil P when there is adequate amount present in the soil (Grant and Flaten 2019). Canola`s tap + fibrous root system is extensive and also capable of acidification of its rhizosphere through the exudation of organic acids which increases P availability (Hoffland, 1992). The canola crop may be able to uptake enough P in early season from the bulk soil if soil P concentration is high. As an alternative strategy for P application, “long-term sustainable” P fertilizer management aims to bring up the soil P to a desired level and maintain target soil test P with additional fertilizer if necessary (Mallarino, 2012.). A study conducted in a Saskatchewan Brown Chernozemic soil found that a single large broadcast application of P fertilization had a long-term positive effect on crop P uptake (Wagar et al., 1986). The research also revealed that seed-row placed P fertilizer had a similar residual effect on the following crop. With this long-term sustainability strategy, only a small amount of P fertilizer may be needed to provide a canola crop with “starter” effect and the rest that would be added to maintain or build soil P fertility could be banded separately from the seed-row (McLaughlin et al., 2011). If the amount of P fertilizer applied in the field is greater than the P removed by the crop, P will accumulate over time. Long-term P fertilization at rates in excess of crop removal can increase the level of soil residual P, which can become available to the crop as a slowly available P source (Syers et al., 2013) as P will move from the non-labile pools to replenish the labile pools in response to plant uptake (Liu et al., 2014). However, the soil P pool is not infinite in its capacity to adsorb and hold P in the solid phase. When the soil P pool reaches its limit, the excess P fertilization may lead to loading of soluble P forms and risk of P movement toward water bodies in run-off water. Therefore, it is critical to sustainability to maintain the target soil P at a level which does not contribute to excess soluble P loss in run-off water.

The current recommendation for the maximum safe rate of seed-placed P fertilizer is 15 lb P_2O_5 ac^{-1} in Alberta, 20 in Manitoba, and 25 in Saskatchewan, which might not be enough for the newer high yielding canola cultivars. A field study in Manitoba where the soil P level was moderate found that canola yield was optimized with ~ 25kg P_2O_5 ha^{-1} P fertilization rate in the year of application (Grant et al., 2009). However, some modern canola cultivars with yield potentials of 70 plus bushels per acre would require more added P than this to achieve their yield potential. Canola is sensitive to seed-placed MAP fertilizer as it can be toxic when concentration near the seed and rootlets of the germinating seed is too high, which can lead to seedling damage, stand reduction and potential yield loss. However, there is no evidence of reduced biomass yield at maturity from the high rate of MAP fertilizer application used on the canola crop in this study. The germination was delayed in some area due to the dry condition where the canola population was affected (Mooleki et al., 2019). However, the compensatory ability of the canola crop overcame the reduction in plant population, resulting in no effect on biomass yield at most locations. The combined data indicated that canola biomass yield was optimized at ~ 56 kg P_2O_5 ha^{-1} (Figure 4.6). Modern hybrid canola cultivars have significantly higher yield potential than older/conventional open pollinated cultivars and greater demand for nutrients including phosphorus (Karamanos and Kruger, 2009). The tolerance level for P fertilizer application in the seed-row may also be greater in the newer canola cultivars.

4.6.2 Opener spread and row spacing

Phosphorus should be placed close to the seed to ensure access to seedling roots, as P will react with calcium and magnesium present in high pH soils and become less available to the plant, especially in calcareous soils of the Northern Great Plains. Broadcast application is the simplest form of P fertilization. However, without incorporation, broadcasting leaves soluble P at the soil surface which can be environmentally harmful when the solubilized P moves into water bodies with rainfall or snowmelt run-off (Li et al., 2011; Smith et al., 2016). Band application is a more effective means for P fertilization as it places fertilizer below the soil surface and close to the roots. Reactions between P fertilizer and soil constituents restrict the movement of the P; and the concentration of P decreases with distance from the point of application (Kar et al., 2012), reducing the concentration gradient that can be set up between a root surface and the P in the soil. A meta-analysis also revealed that band application is more beneficial in suppling relatively immobile nutrients like P to the crop (Nkebiwe et al., 2016).

At Melfort site, the highest P recovery is observed with 1" opener spread with 9" row spacing (Figure 4.7). When placing fertilizer in a furrow, as in seed-row placement, a narrower opener spread would leave a more concentrated band in comparison to a wider opener spread, which gives the crop an opportunity to access more P in surrounding soil solution earlier on following germination. While narrower spread provides the seed with closer association and smaller distance to fertilizer granules which ensures the early accessibility of P, high concentration near seed may become problematic due to injury especially at higher rates. At Scott and Lethbridge site, a wider 4" opener spread has significantly higher biomass yield in comparison to 1" spread. A wider opener spread that provides a greater distance between fertilizer granule and seed t can effectively reduce the P fertilizer concentration around seed and reduce potential damage to the canola crop root system from salt effect as well, lower P fertilizer concentration near the seed may not necessarily reduce the amount of P potentially available to young canola plants. This is because the roots of a vigorous canola plant will rapidly grow outward and access the P fertilizer. Furthermore, having P fertilizer more evenly spread out across the seedbed, as with greater opener spread and narrower row spacing (higher SBU), may encourage the roots to more rapidly extend outward from the seed-row and explore a larger volume of the soil, giving better access to water and other nutrients. In this field study, different opener spreads alone did not have significant impact on canola crop biomass at most of the test sites other than Scott and Lethbridge, which suggest the canola crop can handle relatively high amounts of MAP fertilizer present in the seed row.

In the growth chamber study in chapter 3 under conditions with sufficient moisture and where rooting volume is limited by growing plants in trays, narrow opener spread was better in promoting P uptake presumably due to increased solubility of the P when applied in a concentrated band. However, in the field study, a wider opener spread had no significant effect on canola biomass yield response to P fertilization except at Scott and Lethbridge, which likely reflects the different environmental and rooting conditions between the phytotron and the field. Root growth would not be inhibited as much by the concentrated P fertilizer in a narrow band in the controlled environment chamber where moisture and temperature were sufficient and root exploration ability is limited by the confines of the tray size. In the field, dry and cold conditions may increase the negative impact of the salt effect of the fertilizer on root growth when placed in close association with the seed, and root proliferation around narrow, widely spaced bands may restrict the access of the crop to other nutrients and water.

Row spacing only had significant effect on P uptake and recovery at Lethbridge site where narrower row spacing of 9 " resulted in significantly higher recovery than 12" spacing. This may also reflect impact of less than optimal conditions for germination and early root growth in the field compared to the growth chamber.

4.6.3 Seed bed utilization (SBU)

For seed-row placed fertilizer, SBU is used to describe the degree of fertilizer and seed dispersion, which is calculated as opener spread divided by the row spacing (Roberts & Harapiak, 1997). The SBU is increased with wider opener spread or closer row spacing between the fertilizer bands. A greater SBU indicates the fertilizer is more diluted which reduces the risk of seedling damage but may also increase fertilizer-soil contact and fixation into less available forms. The Canola Council of Canada indicate that greater seed-bed utilization allows higher seed-row placed P fertilizer rates (CCC, 2017). The interaction effect of opener spread and row spacing did not significantly impact canola biomass yield, P uptake, and P recovery at most sites (Table4.4, Figure 4.7). At Lethbridge, better canola crop response was observed with either reduced row spacing, or increased opener spread (greater SBU). However, At Saskatoon and Brooks where the moisture condition was maintained by irrigation, canola biomass yield was significantly increased with wider row spacing, and there was a trend for P uptake and P recovery to increase with wider row spacing, which reduces the SBU (Figure 4.2, 4.3, and 4.4). In the field, overall higher SBU such as 44% where the fertilizer is spread out across a high proportion of the seed bed, appeared to perform better (Figure 4.8). Under field conditions, having greater distribution of the P fertilizer throughout the soil may have advantage by encouraging root extension outward to access P, water and other resources.

5.0 Synthesis and Conclusion

5.1 Overview

Canola responses to P fertilizer application in the seed-row, including biomass yield, P uptake, and recovery were evaluated under controlled environment and field conditions in this thesis. The results of this work fully support the first hypothesis in which canola was postulated to respond positively to seed-row placed P in biomass yield and P uptake. On a P deficient Brown Chernozem soil collected from south-central Saskatchewan, canola (*B. napus* hybrid var LL 252) emergence was not significantly (α=0.05) affected by application of MAP and struvite in the seed-row up to 60 kg P_2O_5 ha^{-1} under a controlled environment condition. The findings do contrast with a previous study by Qian and Schoenau (2010) where canola emergence was found to be significantly reduced at rates of 30-40 kg P_2O_5 ha^{-1} and above. This discrepancy may reflect greater vigor of modern canola varieties and ability to withstand higher rates of seed-row placed P without significant injury. Canola biomass yield 30 days after seeding was significantly increased by the addition of 20 kg P_2O_5 ha^{-1} fertilizer in the seed-row, and mean canola biomass yield was maximized at 40 kg P_2O_5 ha^{-1}, while the P uptake in the above-ground plant material was maximized at the 40 and 60 kg P_2O_5 ha^{-1} rates. Similarly, in the field study, canola (*B. napus* hybrid var L233P) had significant positive response of aboveground biomass yield at physiological maturity to P fertilization at most sites. The 22 kg P_2O_5 ha^{-1} rate of MAP produced the greatest incremental yield increase (increase in yield per unit of fertilizer added), with further yield increases levelling off at higher rates. Across the sites, the canola biomass yield and P uptake was generally maximized at about 56 kg P_2O_5 ha^{-1} (50 lbs P_2O_5 ac^{-1}), with greater responses observed at sites with low soil test P concentrations (e.g. Melfort). No significant negative response was observed on the canola crop biomass up to the highest (73 kg P_2O_5 ha^{-1}) seed-row placed P rate. Both the controlled environment and field study responses observed suggest that 40 kg P_2O_5 ha^{-1} was an appropriate rate in the seed-row to maximize the canola biomass yield without injury concerns. In the chamber study, there was a trend that canola emergence after 5 days decreased from 95 percent to 85 percent with increasing P fertilization rate from 0 to 60 kg P_2O_5 ha^{-1}. The canola emergence had largely recovered by day 10 but the delayed emergence may allow weeds to become competitive for nutrients, water and growing space.

Increasing P uptake beyond the point of maximum yield, as occurred with the higher rates of P addition, may be considered as luxury uptake which produces no economic return from the extra money spent on the P fertilizer purchase in the year of application. However, recycling of P from the straw left after harvest and residual soil P that is built up in the soil over time contributes to P fertility maintenance over the long term. The results from the growth chamber study in Chapter 3 suggest that P fertilizer application at a rate that is more than what is required to maximize canola crop yield in the year of application can benefit the subsequent crops. Both extraction and ion exchange assessment methods of soil residual available P at the end of the canola-wheat-pea rotation indicated increasing residual available P with increasing application rate. However, this crop rotation in the chamber was completed in three months, whereas in the field it would take three years. A longer time period may reduce availability of residual fertilizer P by giving more time to revert to less soluble forms. It has long been known that on low P soil, the buildup of background soil P levels combined with low rates of starter P fertilizer application can provide crops with very good growth benefits (Alessi & Power, 1980). However, the effect and degree of observed benefit from residual fertilizer P will also depend on the following crop type. In the chamber study (Chapter 3), wheat (*Triticum aestivum* hard red spring var Brandon) greatly benefitted from increased residual soil P level, while pea did not show much response, likely as a result of the good P scavenging ability of the pea roots.

Both MAP and struvite fertilizer P forms evaluated in the controlled environment study produced similar canola crop response in 30 days biomass yield, P uptake, and P fertilizer recovery; while pea, as the third crop in the rotation, had no significant response to any treatment. Under the controlled environment conditions of the chamber, the struvite P fertilizer form appeared to be a good alternative P source for canola with benefit to the following crops in the rotation also observed. These findings do not support the second hypothesis of this thesis that struvite would result in reduced yield and crop P utilization response compared to monoammonium phosphate. It appears that despite the lower solubility of struvite compared to MAP in water, that the reaction products produced in soil may be of similar availability and/or crop roots are effective in solubilizing the P forms present. The FTIR analysis was not able to reveal any differences in residual P forms present but further evaluation of fate of P applied as struvite is warranted, especially under field conditions.

The third hypothesis of this thesis, that effects of rate, opener spread, and row spacing treatments would vary with soil and environmental conditions in the field and differ between field and controlled environment was supported by the results of this thesis. Narrower opener spread resulted in a greater canola biomass yield, P uptake, and P recovery in the chamber study, while in the field study at three of the five sites a wider opener spread and overall higher SBU produced better canola response to the seed-row placed MAP. In compare to the controlled environment, a high concentration of fertilizer closer to the seed as occurs in a narrower opener is more likely to negatively affect initial crop root growth in the field where the environmental conditions (moisture, temperature) are less than ideal. In a growth chamber, the soil moisture was maintained at a sufficient level which dilutes the fertilizer in the seed row and reduced the risk of fertilizer burn. Furthermore, a seeding tool configuration with a wide opener spread (e.g. 4”) and narrow row spacing (e.g. 9”) that produces high seed bed utilization of 44% will result in considerable dispersion of seed and fertilizer across the seed bed area. This may encourage early exploration and exploitation of soil rooting volume for resources (nutrients and water), benefiting plant growth. This effect would be manifested more in the field than in a growth chamber tray where the ability of the roots to move outward is inherently restricted by the tray dimensions. In the field study, where environmental and rooting conditions are different from the controlled environment phytotron, a wider opener spread resulted in a significantly greater canola biomass yield response to P fertilization at Scott and Lethbridge. Although placement of P fertilizer in a narrower furrow may increase soil P availability to crops due to reduced soil-fertilizer contact and fixation and give benefit under controlled conditions as revealed in the chamber study, it appears that in the field the apparent effect and benefits are diminished. Under field conditions a wider opener spread and a narrower row spacing (higher SBU) may be beneficial to canola by encouraging early root proliferation outward, covering a greater soil volume to access water and other nutrients.

5.2 Synthesis and Recommendation

In this study canola positively responded in biomass yield and P uptake both at early (30 day) and late (maturity) stages of growth to P fertilizer placed in the seed-row. The tolerance of the canola in the current study to higher rates in the seed-row than in previous studies, and positive responses observed at higher rates suggest that recommended rates may need to be adjusted upwards for new canola varieties. The nearly equivalent performance of struvite to MAP in the crop rotation observed in the controlled environment study indicates that struvite is an effective P fertilizer form in the soil types evaluated. More field studies with struvite on a wider range of soil types is desirable. This study revealed that under the controlled conditions of the phytotron where moisture and temperature are sufficient, a narrow opener spread (e.g. 1" opener) provided the canola crop with more benefits including greater biomass yield, P uptake, and fertilizer P recovery. Also, the following crop was more likely to utilize the residual P that was previously placed in a narrow seed row, where the P added likely had less fixation and sorption. The actual degree of fixation of fertilizer P as affected by spread across a band opener furrow width needs to be verified through identification of P fertilizer reaction products formed, which was beyond the scope of this study. Interestingly, the field study showed an apparent contrasting result to the growth chamber study, where in the field, the wider spread often had greater canola crop biomass, P uptake and fertilizer P recovery. Pre-season soil P level, moisture condition (existing soil water & upcoming rain fall), and temperature are factors affecting canola growth and its ability to utilize and respond to added P fertilizer. In a field condition, especially where soil is cold and moisture is limited, having P fertilizer more evenly distributed in the soil volume (e.g. wider opener spread, narrower row spacing) might encourage more soil volume to be explored by roots in the early growth stages and promote greater access to other nutrients and water. Direct assessment of root growth expansion and distribution as affected by opener configuration would be desirable in future work.

5.3 Future Research

This research addressed gaps in understanding canola response to the P fertilizer placed in the seed-row, especially in understanding how opener spread, row spacing, and overall seedbed utilization affect canola biomass yield, P uptake and fertilizer P recovery. Insight was also provided on how struvite, a new "green" fertilizer P form produced from wastewater streams, performs in comparison to conventional MAP under controlled environment phytotron conditions. Additional information was also obtained on rates of seed-row placed P fertilizer as related to seed-row safety and to maximize yield. As new seeding equipment available today typically offers side-banding and mid-row banding placement options for P fertilizers, a comparison between seed-row banding, side banding and mid-row banding of P fertilizer with different opener spreads would be helpful in refining fertilizer placement method recommendations.

In the chamber study, wheat as the second crop in the rotation had positive biomass response but slightly reduced P uptake response to the residual P from struvite compared to MAP, which may be related to the less soluble nature of the struvite mineral and its reaction products. A detailed evaluation of the P reaction product species formed when MAP and struvite granules undergo dissolution, and their changes over time in the soil as the products age would be beneficial in helping to explain and predict differences in plant yield response and P uptake. Furthermore, many plants can utilize P contained in fertilizer/P minerals that are of low water solubility. The modified Kelowna and ion exchange resin membrane techniques may not be able to detect all the plant available P in the soil. In addition, a k-edge XANES spectroscopy assessment could be useful in soil P mineral speciation in a future study. Unfortunately, the ATR-FTIR spectrum was not able to reveal differences in P forms present in the soil in the current study due to its high detection limit.

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Appendix

Table A-1: ALS environmental analytical report

Sample Details/Parameters	Result	Qualifier*	D.L.	Units	Extracted	Analyzed	Batch
L2231107-1 SHAW PHYTOTRON							
Sampled By: CLIENT on 11-FEB-19 @ 09:00							
Matrix: SOIL							
pH and EC (1:2 Soil:Water Extraction)							
Conductivity (1:2)	0.246		0.050	dS m-1	15-FEB-19	15-FEB-19	R4509959
pH (1:2 soil:water)	7.67		0.10	pH	15-FEB-19	15-FEB-19	R4509959
Particle Size Analysis:Mini-Pipet Method							
% Sand (2.0mm - 0.05mm)	46.2		1.0	%	13-FEB-19	14-FEB-19	R4507553
% Silt (0.05mm - 2um)	35.2		1.0	%	13-FEB-19	14-FEB-19	R4507553
% Clay (<2um)	18.5		1.0	%	13-FEB-19	14-FEB-19	R4507553
Texture	Loam				13-FEB-19	14-FEB-19	R4507553
Available N, P, K and S							
Available Nitrate-N							
Available Nitrate-N	8.1		1.0	mg/kg	15-FEB-19	15-FEB-19	R4510171
Available Sulfate-S							
Available Sulfate-S	8.2		4.0	mg/kg	15-FEB-19	15-FEB-19	R4509950
Plant Available Phosphorus and Potassium							
Available Phosphate-P	10.9		2.0	mg/kg	14-FEB-19	14-FEB-19	R4509487
Available Potassium	454	DLHC	40	mg/kg	14-FEB-19	14-FEB-19	R4509487

Table A-2: Outlier detected by Grubbs test in Canola crop responses at different sites, 2019. Location with an outlier detected are marked with an x.

	Location				
	Saskatoon	Melfort	Scott	Brooks	Lethbridge
Biomass yield	-	-	x	x	x
Treatment	-	-	15 & 23	23	15
Plot	-	-	23 & 3	17	15
P uptake	-	-	-	x	x
Treatment	-	-	-	23	13
Plot	-	-	-	17	25
% P recovery	x	x	x	x	x
Treatment	27	27	8	12	12
Plot	27	11	8	28	9

Table A-3: Saskatoon plot design.

Reducing toxicity of seed-placed phosphorus fertilizer in canola

Plot layout and Dimensions

SASKATOON

Total area	1.3 ha	3.2 ac

80 m

7 m | 66 m | 7 m

20 m

15 m

1.7 m

120 m

160 m

Rep 4																														
Plot	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120
Trt	27	15	8	29	7	22	10	24	14	25	3	12	5	18	26	20	13	9	16	28	2	6	4	21	17	1	30	23	19	11
RS	2	1	1	2	1	2	1	2	1	2	1	1	1	2	2	2	1	1	2	2	1	1	1	2	2	1	2	2	2	1
OW	3	3	2	3	2	2	2	2	3	2	1	3	1	1	3	1	3	2	1	3	1	2	1	2	1	1	3	2	1	3
PR	2	5	3	4	2	2	5	4	4	5	3	2	5	3	1	5	3	4	1	3	2	1	4	1	2	1	5	3	4	1

20 m

Rep 3																														
Plot	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
Trt	3	1	20	13	5	24	7	19	23	26	12	22	15	29	10	27	9	4	21	18	6	14	17	25	8	30	2	28	11	16
RS	1	1	2	1	1	2	1	2	2	2	1	2	1	2	1	2	1	1	2	2	1	1	2	2	1	2	1	2	1	2
OW	1	1	1	3	1	2	2	1	2	3	3	2	3	3	2	3	2	1	2	1	2	3	1	2	2	3	1	3	3	1
PR	3	1	5	3	5	4	2	4	3	1	2	2	5	4	5	2	4	4	1	3	1	4	2	5	3	5	2	3	1	1

20 m

Rep 2																														
Plot	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
Trt	2	19	29	24	30	13	10	21	17	16	28	18	26	22	4	20	12	5	23	7	6	25	9	3	11	8	27	15	1	14
RS	1	2	2	2	2	1	1	2	2	2	2	2	2	2	1	2	1	1	2	1	1	2	1	1	1	1	2	1	1	1
OW	1	1	3	2	3	3	2	2	1	1	3	1	3	2	1	1	3	1	2	2	2	2	2	1	3	2	3	3	1	3
PR	2	4	4	4	5	3	5	1	2	1	3	3	1	2	4	5	2	5	3	2	1	5	4	3	1	3	2	5	1	4

20 m

Rep 1																														
Plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Trt	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
RS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
OW	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
PR	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5

20 m

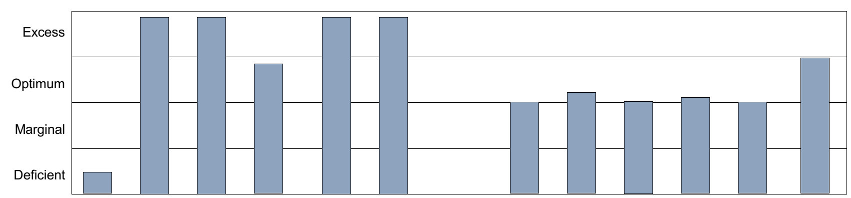
Table A-4: Example of soil analysis result from FarmersEdge laboratory, Winnipeg, MB.

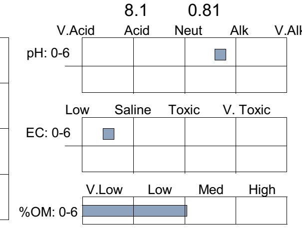
FarmersEdge

Farmers Edge Laboratories
1357 Dugald Road
Winnipeg, Manitoba Canada
R2J 0H3
Phone: 1 204 233 4099

Report To:	AAFC Saskatoon	**Grower:**	Mooleki	**Lot Number:**	191101_181
	107 Science Place	**Grower Field Name:**	SAS Rep 1-1	**Date Sampled:**	2019/05/09
	Saskatoon, SK S7N 0X2	**Reference Field Name:**		**Received Date:**	2019/11/01
		Legal Location:	NE 1-37-5 W3	**Date Reported:**	2020/01/23
Attention:	Patrick Moolecki	**Total Acres:**			
Client ID:	19-0003	**Sampler:**	Mooleki		

Sample ID	Depth	**N** ppm	**P*** ppm	**K** ppm	**S** ppm	**Ca** ppm	**Mg** ppm	**Na** ppm	**B** ppm	**Cu** ppm	**Fe** ppm	**Mn** ppm	**Zn** ppm	**Cl** ppm	**pH**	**EC** dS/m	**OM** %
191101_181-01	0-6	11	87.0	950	9	6600	700	18	0.8	1.7	14.0	6.9	1.1	17.0	7.7	0.96	4.2
191101_181-02	6-12	3			6									7.7	7.7	0.89	
191101_181-03	12-24	2			11									2.6	8.1	0.81	





	N	P	K	S
0-6 lb/Ac:	22	174	1900	17
6-12 lb/Ac:	7			11
12-24 lb/Ac:	8			44
Total lb/Ac measured:	37	174	1900	72
Estimated lb/Ac to 24 inch:	37			72

CEC (meq/100g):	41.0	Ca Base Saturation (%):	80.0	Mg Base Saturation (%):	14.0
Base Saturation (%):	100.0	K Base Saturation (%):	5.9	Na Base Saturation (%):	0.2

Sand (%): 22.0 Silt (%): 38.0 Clay (%): 40.0 Texture: Clay Loam

Recommendation:	Comments:
	* Modified Kelowna Extractable Phosphate

Interpretive Guidelines and Class Limits are based on accepted guidelines. The client is advised to consult with an agronomic professional for detailed interpretation.
Farmer's Edge Laboratories limits liability to the cost of the analysis.

Table A-5: Effect of fertilization rate and its interaction with opener spread on 30-day crop biomass yield and P uptake, and emergence after 5 days. For a crop, means in a column followed by the same letter are not significantly different based on Tukey`s HSD test at $\alpha = 0.05$ level of significance.

			Parameter		
	Opener spread	Rate kg P_2O_5 ha^{-1}	30 d Biomass	30 d P uptake	†5 d Emergence (%)
Canola	1"	0	6.5 b	13.5 d	95a
		20	7.4 ab	17.1 cd	86 a
		40	8.2 a	21.1 ab	91 a
		60	8.2 a	22.5 a	83 a
	3"	0	6.4 b	13.2 d	96 a
		20	7.2 ab	16.3 cd	86 a
		40	7.2 ab	18.1 bc	86 a
		60	6.9 b	17.7 c	84 a
Wheat	1"	0	1.7 de	2.9 d	97 a
		20	2.8 bc	3.8 bcd	94 a
		40	3.2 b	5.0 abc	94 a
		60	4.0 a	5.6 ab	95 a
	3"	0	1.7 e	3.2 cd	98 a
		20	2.0 de	4.5 abcd	96 a
		40	2.3 cd	4.8 abcd	93 a
		60	2.3 cd	6.0 a	87 a
Pea	1"	0	4.3 a	5.3 a	88 a
		20	4.3 a	4.9 a	92 a
		40	4.4 a	5.3 a	88 a
		60	4.3 a	5.4 a	77 a
	3"	0	4.8 a	5.6 a	91 a
		20	4.7 a	5.8 a	91 a
		40	4.6 a	5.6 a	92 a
		60	4.7 a	5.7 a	90 a

† Emergence rate was assessed 5 days after seeding.

Table A-6: Effect of MAP (11-52-0) fertilization rate (kg P_2O_5 ha^{-1}) on canola crop biomass yield, P uptake, and % P recovery in 2019 field study. Means followed by the same letter are not significantly different based on Tukey`s HSD test at α=0.05.

		Fertilization rate					
Location	*Parameter*	0 kg P_2O_5 ha^{-1}	22 kg P_2O_5 ha^{-1}	39 kg P_2O_5 ha^{-1}	56 kg P_2O_5 ha^{-1}	73 kg P_2O_5 ha^{-1}	*p* value
Saskatoon	Biomass yield	10159 ^{a}	10576 ^{a}	10975 ^{a}	10806 ^{a}	10605 ^{a}	0.1358
	P uptake kg ha^{-1}	19.7 ^{a}	21.1 ^{a}	23.1 ^{a}	22.0 ^{a}	21.8 ^{a}	0.1334
	% P recovery	N/A	9.9 ^{a}	20.3 ^{a}	9.4 ^{a}	6.8 ^{a}	0.398
Melfort	Biomass yield	**6530 ^{a}**	**7889 ^{b}**	**7809 ^{b}**	**8674 ^{b}**	**8396 ^{b}**	**0.0001 *** **
	P uptake kg ha^{-1}	**11.9 ^{a}**	**13.9 ^{ab}**	**14.6 ^{bc}**	**15.9 ^{bc}**	**16.5 ^{d}**	**0.0001 *** **
	% P recovery	N/A	18.3 ^{a}	15.7 ^{a}	16.6 ^{a}	14.5 ^{a}	0.8440
Scott	Biomass yield	**8390 ^{a}**	**8742 ^{ab}**	**9385 ^{ab}**	**9820 ^{b}**	**9360 ^{ab}**	**0.0104 ** **
	P uptake kg ha^{-1}	**20.2 ^{a}**	**20.4 ^{a}**	**24.0 ^{ab}**	**25.8 ^{b}**	**24.0 ^{ab}**	**0.0005 *** **
	% P recovery	N/A	25 ^{a}	18.6 ^{a}	18.7 ^{a}	8.7 ^{a}	0.3360
Brooks	Biomass yield	**7323 ^{a}**	**7541 ^{a}**	**8181 ^{ab}**	**7959 ^{ab}**	**9002 ^{b}**	**0.0088 *** **
	P uptake kg ha^{-1}	**13.1 ^{a}**	**14.4 ^{a}**	**15.3 ^{ab}**	**16.1 ^{ab}**	**18.3 ^{b}**	**0.0037 *** **
	% P recovery	N/A	8.0 ^{a}	12.7 ^{a}	12.3 ^{a}	16.4 ^{a}	0.8150
Lethbridge	Biomass yield	3780.5 ^{a}	4224.2 ^{a}	4329.3 ^{a}	4208.8 ^{a}	4286.8 ^{a}	0.1538
	P uptake kg ha^{-1}	**4.1 ^{a}**	**5.0 ^{ab}**	**5.3 ^{b}**	**5.6 ^{b}**	**5.7 ^{b}**	**0.0013 *** **
	% P recovery	N/A	7.3 ^{a}	6.9 ^{a}	5.9 ^{a}	4.5 ^{a}	0.5902
Combined	Biomass yield	**7236 ^{a}**	**7795 ^{ab}**	**8125 ^{ab}**	**8293 ^{b}**	**8355 ^{b}**	**0.0047 *** **
	P uptake kg ha^{-1}	**13.7 ^{a}**	**14.9 ^{ab}**	**16.5 ^{b}**	**17.0 ^{b}**	**17.0 ^{b}**	**0.0013 *** **
	% P recovery	N/A	9.1 ^{a}	14.9 ^{a}	12.6 ^{a}	10.3 ^{a}	0.3230

†Bolded number followed by *** indicates *p-value* < 0.01; ** indicates *p*-value between 0.01 and 0.05; and* indicates p-*value* greater than 0.05 and less than 0.10.

Table A-7: Effect of seed bed utilization (SBU= row spacing divided by opener width) on canola crop biomass yield, P uptake, and % P recovery in 2019 field study.

		SBU					
Location	*Parameter*	8%	11%	17%	22%	33%	44%
Saskatoon	Biomass yield	10995	10360	11052	10398	11042	9899
	P uptake kg ha^{-1}	22.4	22.0	20.9	20.1	23.6	20.2
	% P recovery	14.7	15.3	9.4	4.8	23.5	2.5
Melfort	Biomass yield	7673.2	8206.9	7906.9	7892.3	7864.0	7617.0
	P uptake kg ha^{-1}	14.1	15.4	14.6	14.1	15.1	13.9
	% P recovery	12.4	23.5	19.1	13.4	16.9	12.3
Scott	Biomass yield	8132	8870	9529	9155	9018	10180
	P uptake kg ha^{-1}	20.5	23.0	24.0	21.4	22.6	25.7
	% P recovery	3.4	5.9	18.4	0.7	14.3	30.9
Brooks	Biomass yield	7858	7303	9363	7071	7732	8640
	P uptake kg ha^{-1}	14.8	13.4	16.6	14.4	15.4	18.0
	% P recovery	11.1	2.1	22.2	7.0	11.0	22.4
Lethbridge	Biomass yield	3582.7	4327.2	3794.9	4214.2	3928.5	5193.6
	P uptake kg ha^{-1}	4.5	5.4	4.8	5.3	4.7	6.3
	% P recovery	2.4	6.5	4.4	8.1	4.7	11.9
Combined	Biomass yield	7668.4	7813.5	8306.5	7746.5	7917.2	8318.5
	P uptake kg ha^{-1}	15.3	15.8	15.8	15.0	16.3	16.9
	% P recovery	8.8	10.7	14.6	6.9	13.9	15.9